

Chapter 14

Sensitivity of Reference Evapotranspiration and Soil Evaporation to Climate Change in the Eastern Mediterranean Region



Mehmet Aydın, Tsugihiko Watanabe and Selim Kapur

Abstract Climate data generated by a regional climate model (RCM) under the A2 scenario were used to quantify the evaporative demand of the atmosphere in the Mediterranean region of Turkey in a baseline period (1994–2003) and the future (2070–2079). The daily reference evapotranspiration and bare soil evaporation were computed using the FAO-56 Penman-Monteith and E-DiGOR models, respectively, for both periods. The sensitivity of Penman-Monteith type equations to the major climatic variables was determined. Based on decadal averages, solar radiation, air temperature, and wind-speed were projected to increase from 16.084 to 16.324 MJ m⁻² day⁻¹, from 19.3 °C to 20.7 °C, and from 0.75 to 0.77 m s⁻¹ respectively, by the period of 2070–2079 compared with the baseline period. By contrast, the relative humidity is expected to decrease from 68.1 to 67.5% (equivalent to a 0.9% reduction). The reference evapotranspiration (*E_{to}*) and potential soil evaporation (*E_p*) are projected to increase by 92.0 mm year⁻¹ and 68.6 mm year⁻¹ respectively by the 2070s. Conversely, the actual soil evaporation (*E_a*) is expected to decrease by 49.6 mm year⁻¹ by the same period due to the decrease in rainfall and soil wetness.

The reference evapotranspiration was more sensitive to the net radiation in all seasons; followed by the air temperature in the summer months, and by the relative humidity in the winter months under both the present and future conditions. In terms of the sensitivity coefficients, the *E_p* responded better to the changes in climatic variables than the *E_{to}*. The sensitivity of *E_p* to the key climatic elements varied with the seasons: the net radiation was the most causative variable in the summer, whereas the air temperature and relative humidity were the most influential

M. Aydın, Retired Professor, Mustafa Kemal University, Department of Soil Science and Plant Nutrition, Antakya, Turkey; e-mail: maydin08@yahoo.com.

T. Watanabe, Professor, Kyoto University, Regional Planning Graduate School of Global Environmental Studies, Kyoto, Japan; e-mail: nabe@kais.kyoto-u.ac.jp.

S. Kapur, Retired Professor, Çukurova University, Department of Soil Science and Plant Nutrition, Adana, Turkey; e-mail: kapurs@cu.edu.tr.

variables in the winter. The mean sensitivity coefficients for air temperature and wind-speed are projected to increase from 0.40 to 0.45 and from 0.15 to 0.19 respectively by the period of 2070–2079. A slight change in the sensitivity coefficient for relative humidity is projected. This could be explained by the expected air temperature rise and the increase in wind-speed, followed by a negligible decrease in humidity, which can increase the Ep rate. By contrast, the relative contribution of the net radiation to Ep would decrease in the future with a coefficient decreasing from 0.84 to 0.80. This outcome can be attributed to the proportionally higher increases in air temperature and wind-speed in the future, which would reduce the relative portion of the net radiation.

Keywords Climate change • Evapotranspiration • Sensitivity coefficients
Soil evaporation

14.1 Introduction

One of the major issues of this century is global warming. Many impacts associated with climate change have become evident during recent decades; therefore, the issue of climate change has been the major interest of many interdisciplinary studies. Climate change means not only changes in globally averaged surface temperature, but also changes in atmospheric circulation, in the size and patterns of natural climate variations, and in local weather (US-NAS and Royal Society 2014). General circulation models (GCMs) are useful tools to project the possible future climate with increasing confidence, although many aspects of climate change are still uncertain. The projections of some GCMs are available on the IPCC website <http://ipcc-ddc.cru.uea.ac.uk/>; however, models vary in their projections for the magnitude of the expected warming. Nevertheless, all the models agree that the overall net effect of feedbacks is to amplify warming (US-NAS and Royal Society 2014). The adequate downscaling of GCM projections is necessary to study most impacts of climate change at local to regional scales (Yano et al. 2007). Therefore, finer resolution is essential to resolve climatic features and weather extremes and is also a necessity for any quantitative impact study. Thus, there is a need to make extensive use of regional climate models (RCMs) capable of resolving spatial scales as fine as possible <http://prudence.dmi.dk>.

Surface temperatures and precipitation in most regions vary greatly from the global average because of the geographical location, in particular latitude and continental position (US-NAS and Royal Society 2014). Based on the multi-model projections of the 21st century, precipitation is projected to decrease in the Mediterranean region. By contrast, the models projected a temperature rise by 2100 in the same basin (Fujihara et al. 2008; Giorgi/Lionello 2008; Sanchez-Gomez et al. 2009; IPCC 2013). In arid or semi-arid regions, minor variations in precipitation

and temperature have easily induced significant changes in hydrological processes (Huo et al. 2013). In other words, climate change is likely to have a profound effect on the hydrological cycle, namely precipitation, evapotranspiration and soil moisture (Goyal 2004). An accurate estimation of evapotranspiration is essential to better understand land-atmosphere interactions, since it is an important variable in the hydrological cycle for many applications, such as hydrological modelling, water resources management, crop water requirement, and irrigation schedules. Usually, actual crop evapotranspiration can be derived from reference evapotranspiration (*E_{to}*) by means of appropriate crop and water stress coefficients. Recently, therefore, extensive research efforts have examined the potential impact of climate change on reference evapotranspiration. Briefly, *E_{to}* is a measure of the evaporative demand of the atmosphere independent of crop type, crop development, and management practices (Estevez et al. 2009; Kwon/Choi 2011; Zhang et al. 2011; Herrnegger et al. 2012; Yang et al. 2012; Huo et al. 2013; Li et al. 2013; Terink et al. 2013; Ebrahimpour et al. 2014).

Similarly, the evaporation from bare soils is the link between the atmosphere and soil surface in the water cycle; and it is a key issue in the hydrological processes, which are linked to water fluxes in the soil (Romano/Giudici 2009; Vanderborght et al. 2010). That is to say, quantification of the evaporation from bare soils is critical in the physics of land-surface processes, because soil evaporation is an important component of the water balance and the surface energy balance (Bittelli et al. 2008; Allen 2011; Xiao et al. 2011). Agam et al. (2004) concluded that during dry seasons, the latent heat flux played a major role in the dissipation of the net radiation. Potential evaporation from bare soil (hereafter, potential soil evaporation) is similar to evaporation from open-water surface, and it is independent of the soil water content. However, under natural conditions, the soil surface is usually not at, or near saturation. Therefore, the actual evaporation from the bare soil (in brief, actual soil evaporation) is largely dependent on the soil water content, in addition to meteorological conditions (Ayдын et al. 2015). In this context, it is essential to know the impacts of climate change on the components of soil-water balance and to use the information for developing adaptations in water use and soil-water management. However, these impacts have not been conclusively determined.

On the other hand, sensitivity analysis is important in understanding the impacts of climatic variables on evaporation or evapotranspiration. Several leading studies have assessed the parameter of sensitivity for vegetation or open-water surfaces (McCuen 1974; Saxton 1975; Coleman/DeCoursey 1976; Beven 1979). Although many studies to determine the effects of climatic variables on evapotranspiration have been conducted for sensitivity analysis of the Penman-Monteith equation (Beven 1979; Goyal 2004; Gong et al. 2006; Estevez et al. 2009; Kwon/Choi 2011; Huo et al. 2013), studies on the sensitivity of the same model for potential soil evaporation are rare in the literature (Ayдын/Keçecioglu 2010; Ayдын et al. 2015). Although many aspects of climate change are still unpredictable, particularly at site scale and regional level (Zhang/Liu 2005), numerous studies have been carried out

on the regional and seasonal behaviour of the sensitivity of reference evapotranspiration to climate change in recent years (Rana/Katerji 1998; Hupet/Vanclooster 2001; Goyal 2004; Huo et al. 2013; Xie/Zhu 2013; Tabari/Hosseinzadeh-Talae 2014; Xing et al. 2014; Xu et al. 2014). However, to our knowledge, there is no (or very limited) data available on the sensitivity of evaporation and evapotranspiration to climate change in the Mediterranean region of Turkey. In the present chapter, therefore, an attempt has been made to study the sensitivity of reference evapotranspiration and soil evaporation to the major climatic variables such as radiation, air temperature, relative humidity, and wind-speed under the current and projected future conditions.

14.2 Materials and Methods

14.2.1 Study Area and Climate Data

The study station (36°59'N, 35°18'E) is located in the Adana province on the Eastern Mediterranean coast of Turkey. The soils in the region are predominantly fine-textured. A typical Mediterranean climate prevails in the study area, with mild rainy winters and hot dry summers. The long-term mean annual temperature at the site is 18.5 °C. The temperature extremes are −6.4 °C in February and 44.0 °C in July. The mean annual precipitation is about 700 mm, and the mean relative humidity is 66%. About 87% of precipitation occurs during the winter (November–May) (<http://meteor.gov.tr/>). The observed climate data for the study area were obtained from the Turkish State Meteorological Service (DMI). The mean monthly climatic data prevailing in the evaporative demand of the atmosphere for the period of 1994–2003 are given in Fig. 14.1. The mean monthly air temperature was calculated by adding up the daily mean temperatures for each day of a month and then dividing that sum by the number of days in the month. Solar radiation and the mean air temperature were higher, but precipitation was lower during the summer than the winter. A seasonal variation of relative humidity was observed, and the maximum and minimum wind-speed (2 m height) occurred in February and August respectively.

The climate data derived by a RCM have been used in the present chapter, where the RCM projections were based on a newly suggested approach (Pseudo Warming) using re-analysis data (Kimura/Kitoh 2007). The forcing data for the boundary condition of the RCM are given by two GCMs (MRI-CGCM2 and CCSR/NIES-CGCM) for the A2 scenario in the SRES (Yukimoto et al. 2001; Kitoh et al. 2005). Climate change scenarios were created by superimposing projected anomalies on observed climate data of the baseline period (1994–2003). Temperature changes have been added as absolute changes to the baseline series; the other climate parameters have been adapted according to their relative changes (Tao et al. 2003; Dhungana et al. 2006; Yano et al. 2007). The future (2070–2079)

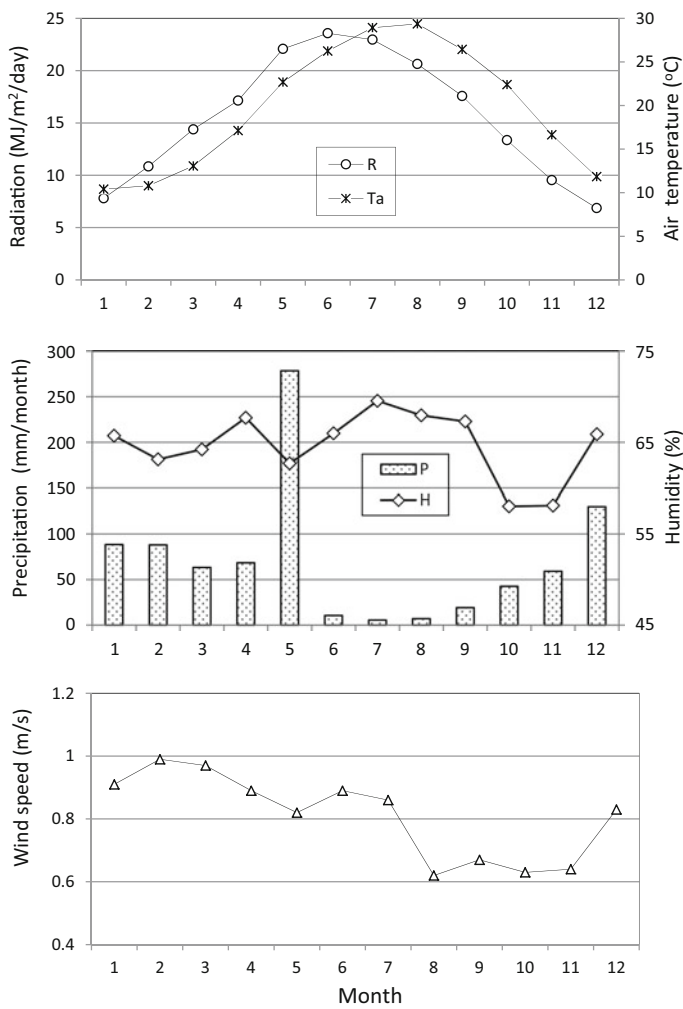


Fig. 14.1 Mean monthly-observed climatic data of the study area for the baseline period (1994–2003) [R: Radiation, Ta: Air temperature, P: Precipitation, H: Humidity]. *Source* The authors

climate changes have been applied to the available baseline climate series in a straightforward way by using the daily data for the baseline period.

14.2.2 Model Descriptions

Evaporation from bare soils can be estimated using the E-DiGOR model, which incorporates the quantification of runoff, drainage, actual soil evaporation, and soil

water storage (Aydın 2008; Aydın et al. 2014). Potential soil evaporation is commonly computed using the classic Penman-Monteith equation, with a surface resistance of zero (Allen et al. 1994; Wallace et al. 1999; Aydın et al. 2005). The Penman-Monteith equation can be simplified to estimate the potential evaporation from a bare soil surface for a 24-hour time step by assuming a standardised height for wind-speed, temperature, and humidity measurements at 2.0 m (Aydın et al. 2015):

$$E_p = \frac{\Delta(R_n - G_s) + 0.1248\rho c_p u_2 e_s \left(1 - \frac{H}{100}\right)}{\lambda(\Delta + \gamma)} \quad (14.1)$$

where E_p is the potential soil evaporation (mm day^{-1}), Δ is the slope of saturated vapour pressure-temperature curve ($\text{kPa } ^\circ\text{C}^{-1}$), R_n is the net radiation ($\text{MJ m}^{-2} \text{day}^{-1}$), G_s is the soil heat flux ($\text{MJ m}^{-2} \text{day}^{-1}$), ρ is the air density (kg m^{-3}), c_p is the specific heat of air ($\text{kJ kg}^{-1} ^\circ\text{C}^{-1} = 1.013$), u_2 is the wind-speed (m s^{-1}) at 2.0 m height, e_s is the saturation vapour pressure (kPa), H is relative humidity (%), λ is the latent heat of vaporisation (MJ kg^{-1}), and γ is the psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$).

Then, the actual soil evaporation can be calculated by the Aydın equation (Aydın et al. 2005; Bellot/Chirino 2013):

$$E_a = \frac{\text{Log}|\psi| - \text{Log}|\psi_{ad}|}{\text{Log}|\psi_p| - \text{Log}|\psi_{ad}|} E_p$$

If $|\psi| \leq |\psi_p|$, then $E_a = E_p$ or $E_a/E_p = 1$ (14.2)

For $|\psi| \geq |\psi_{ad}|$, $E_a = 0$

Note that $E_p \geq 0$

where E_a is the actual soil evaporation (mm day^{-1}), $|\psi_p|$ is the absolute value of soil water potential (matric potential) at which actual evaporation starts to drop below potential one (cm of water), $|\psi_{ad}|$ is the absolute value of soil water potential at air-dryness (cm), which can be defined as the water potential of the soil dried to an air-dry state (Aydın et al. 2015), and $|\psi|$ is the absolute value of the soil water potential at the surface layer (cm).

The soil water potential at the top surface layer is estimated using the Aydın and Uygur equation (Aydın et al. 2008):

$$\psi = - \left[\frac{(1/\alpha)(10 \sum E_p)^3}{2(\theta_{fc} - \theta_{ad})(D_{av}t/\pi)^{1/2}} \right] \quad (14.3)$$

where ψ is the soil water potential (cm of water) at the top surface layer, α is a soil specific parameter (cm) related to flow path tortuosity in the soil, $\sum E_p$ is the cumulative potential soil evaporation (cm), θ_{fc} and θ_{ad} are the volumetric water content ($\text{cm}^3 \text{cm}^{-3}$) at field capacity and air-dryness respectively, D_{av} is the average

hydraulic diffusivity ($\text{cm}^2 \text{ day}^{-1}$) determined experimentally, t is the time (day), and π is 3.1416.

The minimum water potential at the dry soil surface can be derived from the Kelvin equation (Brown/Oosterhuis 1992; Aydin et al. 2005; Aydin 2008):

$$\psi_{ad} = \frac{R_g T}{mg} \ln H_r \quad (14.4)$$

where ψ_{ad} is the water potential for air-dry conditions (cm of water), T is the absolute temperature (K), g is the acceleration due to gravity (981 cm s^{-2}), m is the molecular weight of water ($0.01802 \text{ kg mol}^{-1}$), H_r is the relative humidity of the air (fraction), and R_g is the universal gas constant ($8.3143 \times 10^4 \text{ kg cm}^2 \text{ s}^{-2} \text{ mol}^{-1} \text{ K}^{-1}$).

The Penman-Monteith method, considering aerodynamic resistance and surface resistance, has been successfully used to calculate evapotranspiration from different land covers (Gao et al. 2012). The FAO-56 Penman-Monteith (hereafter, FAO56-PM) equation (Allen et al. 1998) may be written as (Aydin et al. 2015):

$$Et_O = \frac{0.408\Delta(R_n - G_s) + \gamma \frac{900}{T_a + 273} u_2 e_s \left(1 - \frac{H}{100}\right)}{\Delta + \gamma(1 + 0.34u_2)} \quad (14.5)$$

where Et_O is the grass reference evapotranspiration (mm day^{-1}), and T_a is the mean daily air temperature ($^{\circ}\text{C}$). Since the magnitude of daily soil heat flux beneath the grass reference surface is relatively small, G_s can be ignored (Allen et al. 1998).

14.2.3 Sensitivity Analysis

There are different ways of computing sensitivity coefficients for climate variables (Goyal 2004; Gong et al. 2006; Irmak et al. 2006; Estevez et al. 2009; Huo et al. 2013). In this study, the non-dimensional relative sensitivity coefficients were calculated following McCuen (1974) and Beven (1979):

$$S_i = \frac{\partial O}{\partial V_i} \cdot \frac{V_i}{O} \quad (14.6)$$

here S_i represents the fraction of change in variable V_i , transmitted to the change in output O .

Based on the quotient rule for derivatives and Eq. (14.6), the derived formulas for the relative sensitivity coefficients (S) of the variables in Eq. (14.1) are as follows (Aydin et al. 2015):

$$S_{R_n} = \frac{\Delta R_n}{\Delta(R_n - G_s) + 0.1248\rho c_p u_2 e_s (1 - \frac{H}{100})} \quad (14.7)$$

$$S_H = \frac{-H/100}{\frac{\Delta(R_n - G_s)}{0.1248\rho c_p u_2 e_s} - \frac{H}{100} + 1} \quad (14.8)$$

$$S_{u_2} = \frac{1}{\frac{\Delta(R_n - G_s)}{0.1248\rho c_p u_2 e_s (1 - \frac{H}{100})} + 1} \quad (14.9)$$

The sensitivity function related to the air temperature (T_a) can be approximated by (see: McCuen 1974):

$$\frac{dE_p}{dT_a} = \Delta \frac{dE_p}{d\delta} \quad (14.10)$$

Here, δ is the vapour pressure deficit of the air (kPa). S_{T_a} can found as:

$$S_{T_a} = \frac{\Delta T_a}{\frac{\Delta(R_n - G_s)}{0.1248\rho c_p u_2} + e_s (1 - \frac{H}{100})} \quad (14.11)$$

Aydın et al. (2015) reported that the contribution of the soil heat flux (G_s) to daily evaporation was negligible, and G_s could not be considered in the sensitivity analysis.

Similarly, the derivative approach can be used to calculate the relative sensitivity coefficients (*S) of the variables in Eq. (14.5):

$$^*S_{R_n} = \frac{0.408\Delta R_n}{0.408\Delta R_n + \gamma \frac{900}{T_a + 273} u_2 e_s (1 - \frac{H}{100})} \quad (14.12)$$

$$^*S_H = \frac{-H/100}{\frac{0.408\Delta R_n}{\gamma \frac{900}{T_a + 273} u_2 e_s} - \frac{H}{100} + 1} \quad (14.13)$$

$$^*S_{u_2} = \frac{1}{\frac{0.408\Delta R_n}{\gamma \frac{900}{T_a + 273} u_2 e_s (1 - \frac{H}{100})} + 1} - \frac{0.34u_2\gamma}{\Delta + \gamma(1 + 0.34u_2)} \quad (14.14)$$

$$^*S_{T_a} = \frac{T_a \frac{df(T_a)}{dT_a}}{0.408\Delta R_n + \gamma \frac{900}{T_a + 273} u_2 e_s (1 - \frac{H}{100})} - \frac{T_a \frac{dg(T_a)}{dT_a}}{\Delta + \gamma(1 + 0.34u_2)} \quad (14.15)$$

where $\frac{df(T_a)}{dT_a}$ and $\frac{dg(T_a)}{dT_a}$ are the derivatives of the numerator and denominator of Eq. (14.5) with respect to air temperature (T_a) respectively, and are given below in full (Aydın et al. 2015):

$$\frac{df(T_a)}{dT_a} = \frac{1021.29R_n \left(4098.17e^{\frac{17.27T_a}{T_a+237.3}} - 2(T_a+237.3)e^{\frac{17.27T_a}{T_a+237.3}} \right)}{(T_a+237.3)^4} + \frac{549.72\gamma \left(1 - \frac{H}{100} \right) u_2 \left(\frac{4098.17(T_a+273)e^{\frac{17.27T_a}{T_a+237.3}}}{(T_a+237.3)^2} - e^{\frac{17.27T_a}{T_a+237.3}} \right)}{(T_a+273)^2} \quad (14.16)$$

$$\frac{dg(T_a)}{dT_a} = \frac{2503.16 \left(4098.17e^{\frac{17.27T_a}{T_a+237.3}} - 2(T_a+237.3)e^{\frac{17.27T_a}{T_a+237.3}} \right)}{(T_a+237.3)^4} \quad (14.17)$$

The non-dimensional relative sensitivity coefficients, as defined by Eqs. (14.7)–(14.17), were calculated on a daily basis for net radiation, air temperature, relative humidity, and wind-speed, using climatic data of the baseline (1994–2003) and future (2070–2079) periods. Monthly average sensitivity coefficients were obtained, by averaging daily values. Changes in stomatal resistance to enhanced CO₂ concentration have not been considered in the sensitivity analysis.

In order to simplify the outline of main processes, particularly for readers, and to better understand the frame of our discussion in this chapter, a flow-chart is

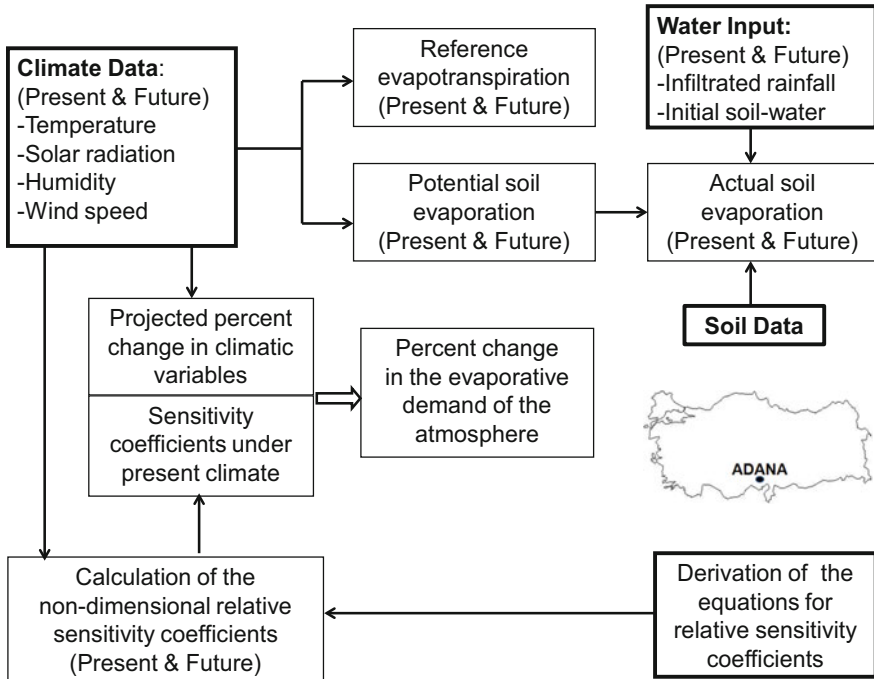


Fig. 14.2 The outline of the main processes and target elements under the Adana conditions.
Source The authors

depicted in Fig. 14.2. It is a very well-known fact that the reference evapotranspiration (E_{tO}) is based on a hypothetical grass surface, where an actual land-surface and soil parameter is not used. Similarly, the potential soil evaporation (E_p) is based on a hypothetical uniform soil structure; and it is dependent on the climatic variables except albedo and soil heat flux, which are the only non-climatic parameters. This means that both E_{tO} and E_p can serve the purpose of comparison of the climatic conditions, as well as the sensitivity to the climatic variables. However, the actual soil evaporation (E_a) is a soil controlled process in addition to climatic conditions.

14.3 Results and Discussion

Daily climatic data necessary for computing the evaporative demand of the atmosphere were downscaled by the RCM. As mentioned in Sect. 14.2.1, the RCM projections were compared to the ten-year observed data of the baseline period (1994–2003). The created data for the baseline period and projected changes in their magnitudes in the future (2070–2079) are given in Fig. 14.3. Based on decadal averages, solar radiation, air temperature, and wind-speed are projected to increase from 16.084 to 16.324 MJ m⁻² day⁻¹, from 19.3 to 20.7 °C, and from 0.75 to 0.77 m s⁻¹ (equivalent to 1.5%, 7.3%, and 2.7%) respectively by the period 2070–2079. By contrast, the mean annual precipitation and relative humidity are expected to decrease from 658.9 to 356.2 mm and from 68.1 to 67.5% (equivalent to 45.9% and 0.9% reduction) respectively by the 2070s when compared with the baseline period. This reveals that the earlier version of the RCM with a grid distance of 25 km had projected a drastic decrease in precipitation which consequently may not be reliable.

The computations of the daily reference evapotranspiration (E_{tO}), and potential (E_p) and actual (E_a) soil evaporations were made for each of the years during the decades of 1994–2003 and 2070–2079 using the data set of daily solar radiation, air temperature, relative humidity and wind-speed of each period. The graphical illustration of the daily data for the entire periods is not presented here since it would have required a lot of space. Instead, the magnitudes of the annual E_{tO} , E_p , and E_a under the current and future climatic conditions are compared in Fig. 14.4. Both E_{tO} and E_p are projected to increase in the future, in response to the changes in climatic variables such as solar radiation, air temperature, relative humidity, and wind-speed by the 2070s, as predicted by the RCM. Both potential rates (E_{tO} and E_p) represent the evaporative demand of the atmosphere (Aydın et al. 2008). By contrast, the annual E_a is projected to decrease by the period of 2070–2079 compared with the period of 1994–2003 due to lower precipitation and consequently increased soil dryness in the future. The atmospheric evaporative demand and actual soil evaporation denoted noticeable inter-annual fluctuations.

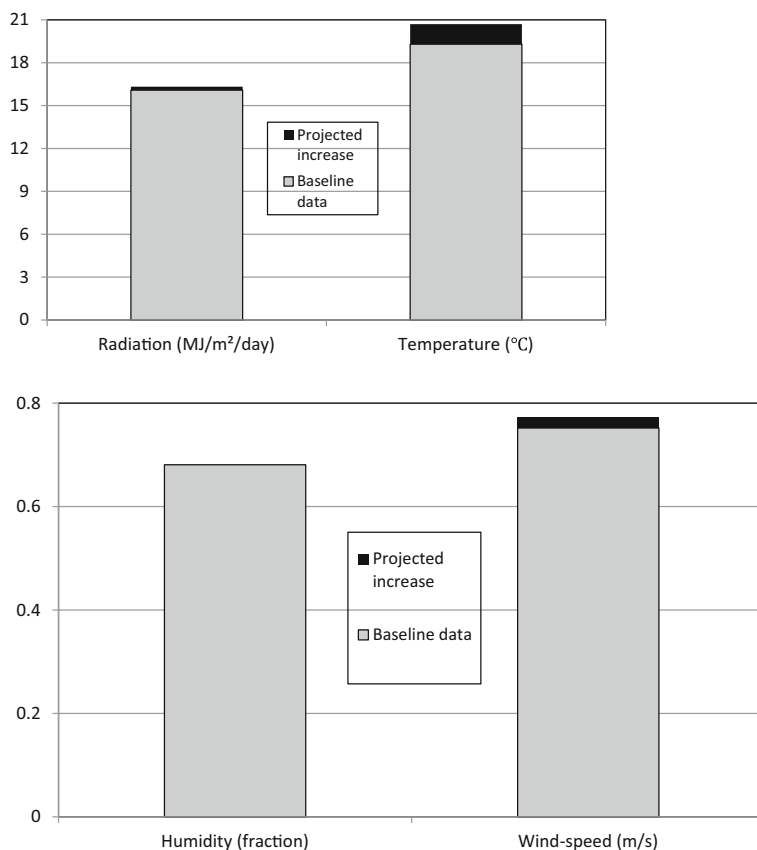


Fig. 14.3 The created climatic data for the baseline period (1994–2003) and projected changes in their magnitudes in the future (2070–2079), as the average over ten years. *Source* The authors

A comparison of the mean monthly E_{to} , E_p , and E_a for the periods of 1994–2003 and 2070–2079 is given in Fig. 14.5, along with mean annual values. The seasonal variations in each component revealed similar patterns in the baseline period and the future. The rates of E_{to} were greater than those of E_p . Although both E_{to} and E_p are used to determine the evaporative power of the atmosphere, the differences in their magnitudes can be attributed to the influences of the surface types. In other words, the dissimilarities in the aerodynamic resistance of the above surfaces, the surface resistance, radiation reflection (albedo), heat storage and transfer of the media, and leaf area index etc., may produce obvious differences in water-loss from the bare soils and from the soils beneath a canopy. Both E_{to} and E_p were higher during the summer months than the winter months under the present and future climate. By contrast, E_a rates were very low in the summer and high in the spring months, depending on soil wetness. That is to say, on the one hand, the size of rainfall events may play a key role in the magnitude of the actual soil

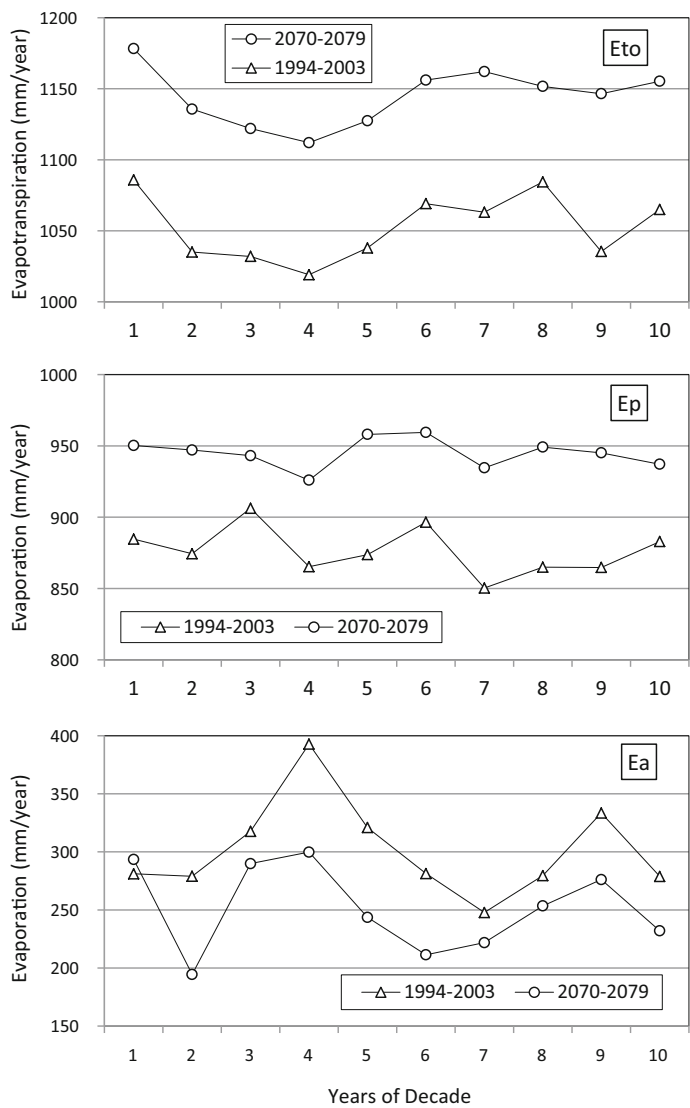


Fig. 14.4 Trends in annual reference evapotranspiration (*Eto*), and potential (*Ep*) and actual (*Ea*) soil evaporations under the climatic conditions of baseline and future decades. *Source* The authors

evaporation; but on the other hand, the variations in the actual soil evaporation may reflect the effects of the rainfall pattern. Unlike *Ep*, the *Ea* is largely influenced by soil wetness. In other words, the magnitude of *Ea* is strongly related to the temporal rainfall pattern, because the contribution of rainfall to the soil water content is considerably dependent on the size of the rainfall events (Aydın et al. 2015). The mean annual *Eto* and *Ep* are projected to increase by 92.0 mm and 68.6 mm

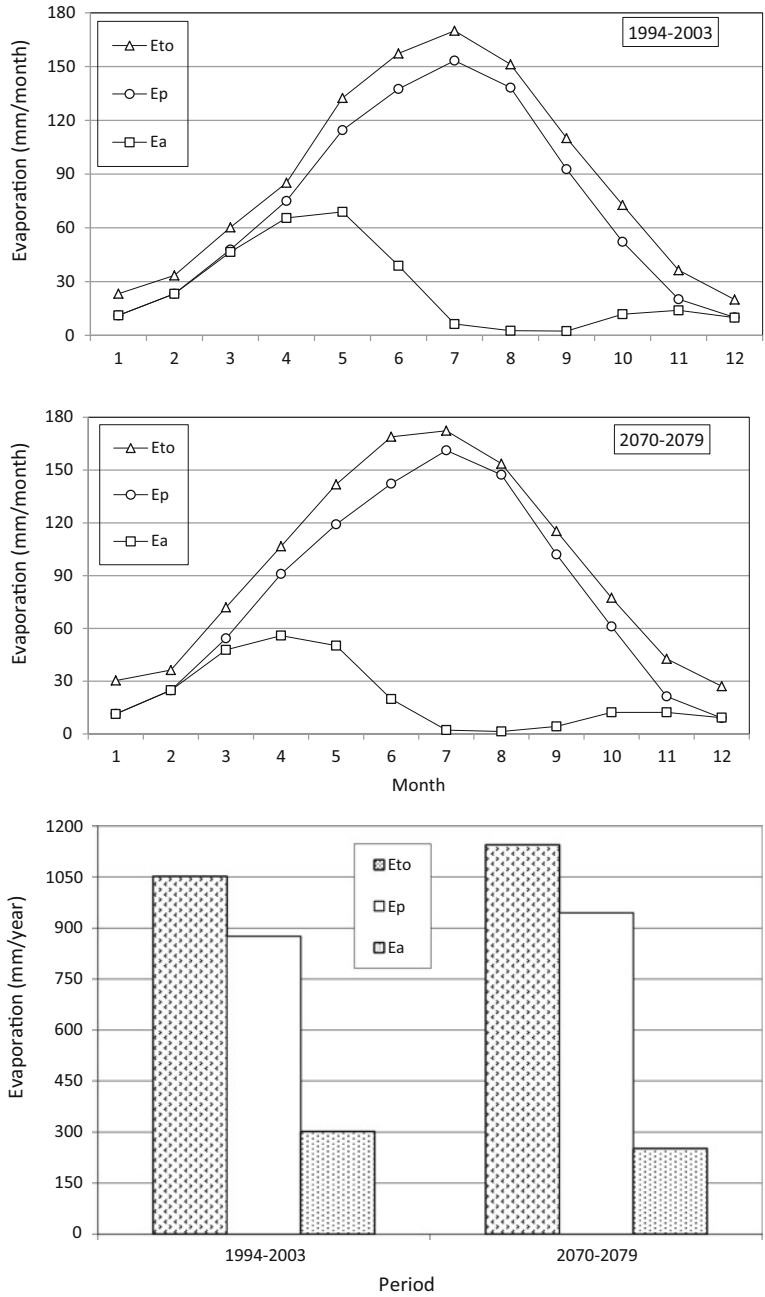


Fig. 14.5 Changes in mean monthly and ten-year average reference evapotranspiration (*Eto*), and potential (*Ep*) and actual (*Ea*) soil evaporations under the climatic conditions of baseline and future periods. *Source* Modified from Aydın et al. (2008: 128)

respectively in the future. By contrast, the mean annual Ea is projected to decrease by 49.6 mm, as also reported by Aydın et al. (2008) together with the high discrepancy observed between the Ep and Ea during the dry summer. Under wet conditions (i.e., winter months), however, the Ea rates were very close to the Ep rates.

The sensitivity coefficients of the major climatic variables are shown in Figs. 14.6 and 14.7. For example, a sensitivity coefficient of 0.4 for a climatic variable would suggest that a 20% increase of that variable, while the other variables are held constant, may increase a dependent variable (Eto or Ep) by 8%. Negative coefficients would indicate that a reduction in a dependent variable would result from an increase in that climatic variable. In evaporation studies, the sensitivity coefficients may vary day-by-day, being dependent on the current values of all the independent variables, and the value of the dependent variable (Beven 1979).

Reference evapotranspiration was more sensitive to the net radiation in all seasons, followed by the air temperature in the summer months, and by the relative humidity in the winter months under both the present and future conditions. The response of Eto to the same climatic variables revealed no considerable difference between the present and future, based on decadal averages (Fig. 14.6). The sensitivity of potential soil evaporation to the key climatic elements varied with seasons: the net radiation was the most causative variable in the summer, while the air temperature and relative humidity were the most influential variables in the winter (Fig. 14.7). The mean sensitivity coefficient related to air temperature is projected to increase from 0.40 to 0.45 by the period of 2070–2079. Similarly, the mean sensitivity coefficient for wind-speed is expected to increase from 0.15 to 0.19 by the 2070s. A slight change in the sensitivity coefficient for relative humidity is also noted. This could be explained by the expected air temperature rise and the increase in wind-speed, followed by a negligible decrease in humidity, which can increase the Ep rate. By contrast, the relative contribution of the net radiation to Ep would decrease in the future with a coefficient reducing from 0.84 to 0.80 (Fig. 14.7). This pattern can be attributed to the proportionally higher increases in the air temperature and wind-speed in the future, which would reduce the relative portion of the net radiation. The results for Ep are not directly comparable to those of the previous works, due to the differences in the analysed equations, whereas different approaches have been used in the literature to conduct the sensitivity analyses and to derive and define the coefficients (Estevez et al. 2009; Ambas/Baltas 2012). In spite of this fact, the order of sensitivity coefficients for major climatic variables transmitted to Ep in this study, is similar to that reported by Aydın et al. (2015) using climate data of seventeen meteorological stations of South Korea. Bearing in mind that our results are based on the Penman-Monteith type equations, in all decades the wind-speed was the least sensitive variable in both Eto and Ep . Gong et al. (2006), analysing the sensitivity of the FAO56-PM model, also found lower sensitivity coefficients for wind-speed. In the present study, based on the mean decadal coefficients, both Eto and Ep were more sensitive to net radiation, followed by air temperature, relative humidity and wind-speed. Contradictory results can be found in the literature, as is the case in the studies conducted by Huo et al. (2013) and Li

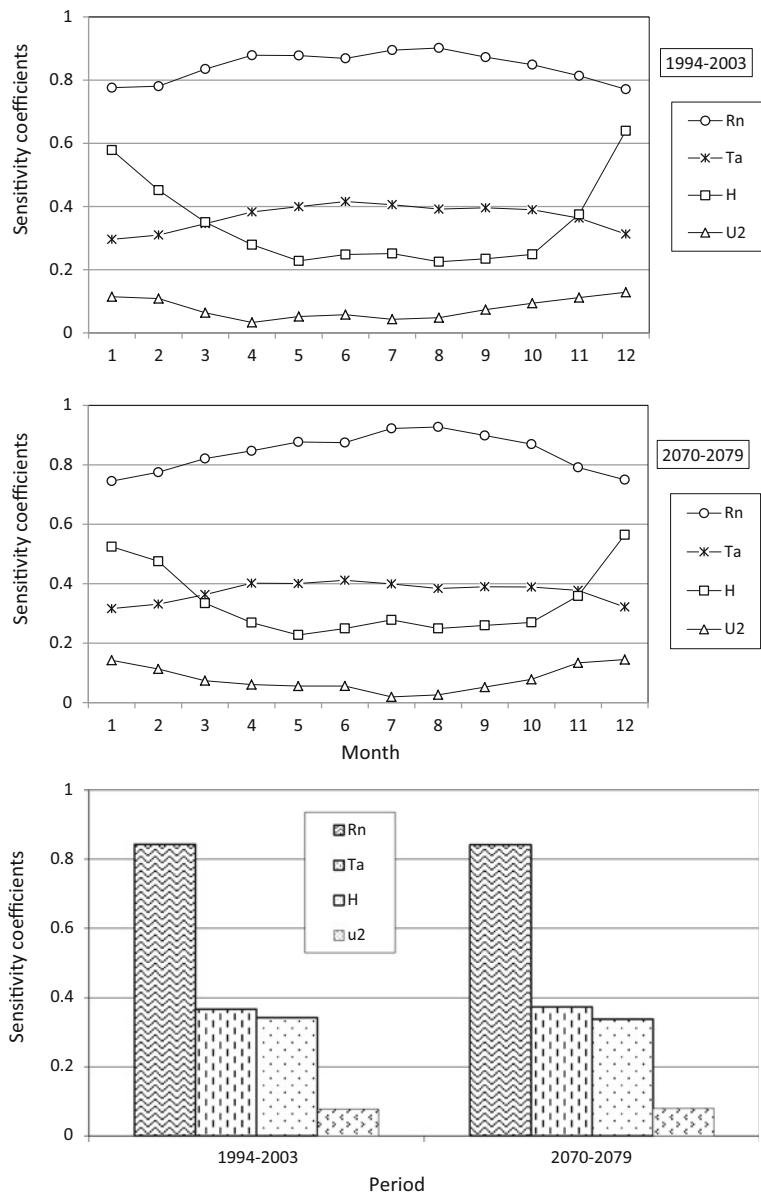


Fig. 14.6 The sensitivity coefficients for net radiation (Rn), air temperature (Ta), relative humidity (H), and wind-speed (u_2), transmitted to E_{to} in baseline and future periods (the coefficients for H were multiplied by -1 , to facilitate visual comparison). *Source* The authors

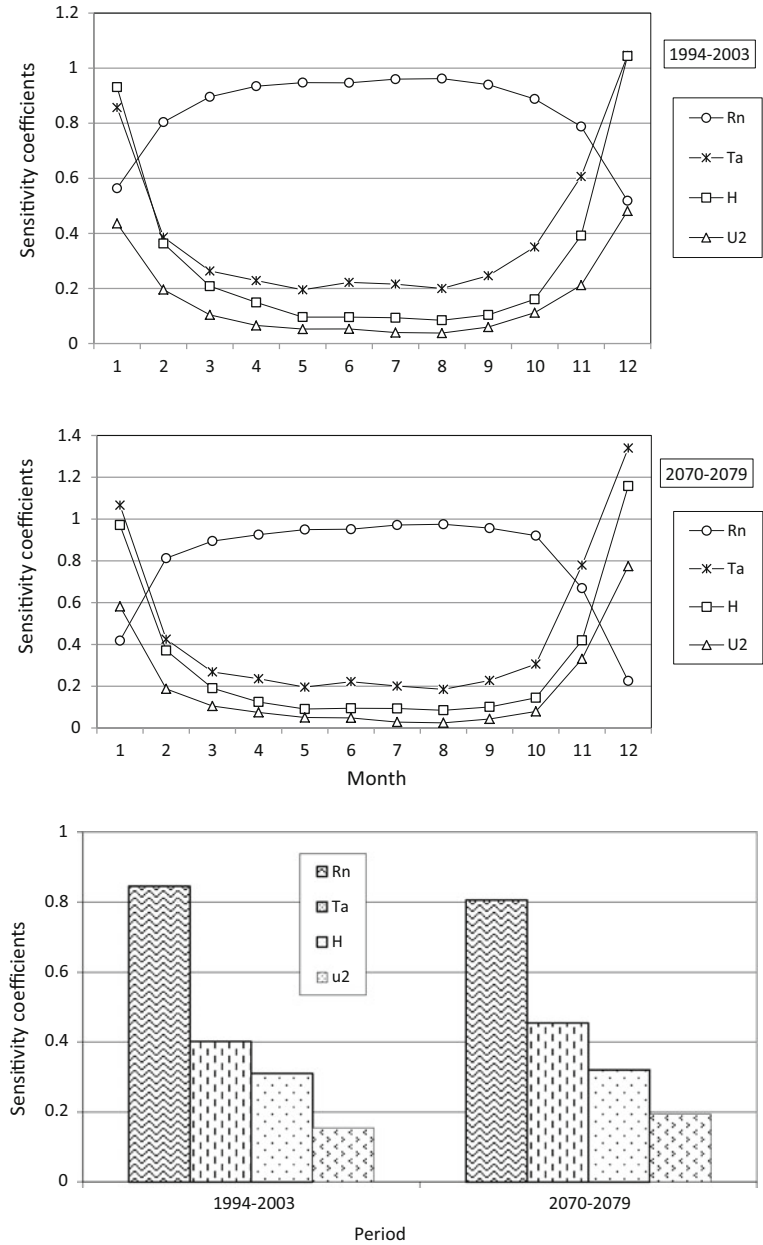


Fig. 14.7 The sensitivity coefficients for net radiation (Rn), air temperature (Ta), relative humidity (H), and wind-speed (u_2), transmitted to Ep in baseline and future periods (the coefficients for H were multiplied by -1 , to facilitate visual comparison). *Source* The authors

et al. (2013), who report that in some regions of China the wind-speed was the most sensitive meteorological variable for *Eto*, followed by relative humidity, temperature, and radiation. In the same country, Xing et al. (2014) indicated that radiation was mainly responsible for the *Eto* change in the southern and eastern basin of the Haihe River, whereas relative humidity and wind-speed were the leading factors in the eastern coastal and northern area. Kwon/Choi (2011) found that in Korea, vapour pressure had the highest influence on *Eto*, followed by wind-speed and radiation. By contrast, Goyal (2004) noted that in an arid region of India *Eto* was sensitive to temperature and net radiation, followed by wind-speed and vapour pressure. Some other studies (McCuen 1974; Saxton 1975; Coleman/DeCoursey 1976; Beven 1979) showed that potential evaporation/evapotranspiration was much more sensitive to radiation, humidity, and temperature. According to the research findings of Tabari/Hosseinzadeh-Talaei (2014), the *Eto* was most sensitive to air temperature in an arid climate compared with semi-arid and humid climates; similarly, the sensitivity of *Eto* to wind-speed decreased from an arid to a humid climate. In contrast to the pattern of air temperature and wind-speed, the sensitivity of *Eto* to sunshine duration increased from an arid to a humid environment. In this regard, Estevez et al. (2009) indicated that the sensitivity of evapotranspiration to the same climatic variables could vary with location. Similarly, Aydın et al. (2015) reported that the influence of the variables to evapotranspiration (or evaporation) was not the same for each period; and the order of the variables changed with geographical positions. They emphasised that, in general, the *Ep* was more sensitive to net radiation, while the *Eto* was mostly affected by relative humidity.

In brief, the sensitivity coefficients change temporally and spatially, because they are, in themselves, sensitive to the relative magnitudes of all the independent (climatic) and dependent (*Ep* or *Eto*) variables. On the other hand, the sensitivity coefficients can be used to predict the change in the atmospheric demand for water vapour in response to the expected changes in climatic variables. As an example, the change in the evaporative demand of the atmosphere in the future was calculated by summing up the contribution of each climatic variable, based on their sensitivity coefficients and percentage change in their magnitudes. Significant effects can be produced by several combined variables acting in a concerted mode in sensitivity studies. Nonetheless, the combined effects can be larger than the sum of the individual effects of all the variables, because changes in more than one variable are likely to occur at the same time in nature (Gong et al. 2006). An increase of $44.3 \text{ mm year}^{-1}$ appeared in the evaporative demand by the 2070s compared with the baseline period, regardless of changes in *Eto* and *Ep* with different rates. Unfortunately, the reliability of the sensitivity coefficients for the future period, depends on the accurate estimates of future climate data. Atmospheric temperature is the most widely used indicator of climatic change in both global and regional scales (Moratiet et al. 2010). However, according to the US-NAS and Royal Society (2014), “several major issues make it impossible to give precise estimates of how global or regional temperature trends will evolve decade by decade into the future.” In addition, there has been a widespread expectation that evaporation would increase as air temperature increases. Paradoxically, despite the

observed rises in average temperature, observations from the Northern Hemisphere show that the rate of pan evaporation has been steadily decreasing over the past fifty years (Roderick/Farquhar 2004; Pockley 2009). Therefore, the changes in all the major climatic variables must be taken into account in evaporation studies to make more robust predictions about future changes in the hydrological cycle (Roderick/Farquhar 2002).

14.4 Conclusions

Solar radiation, air temperature, and wind-speed are projected to increase, while the relative humidity is expected to slightly decrease by the period of 2070–2079 compared with the baseline period (1994–2003). The drastic decrease in future precipitation predicted by the RCM with a grid distance of 25 km may be questionable. Climate change may affect soil dryness doubly, since the evaporative demand of the atmosphere increases at the same time that precipitation decreases. Unlike the reference evapotranspiration (E_{to}) and potential soil evaporation (E_p) projected to increase due to the elevated evaporation requirements, the actual soil evaporation (E_a) is projected to decrease due to the increased soil dryness. Considerable discrepancy between the E_p and E_a was observed during the dry seasons. The sensitivity of the E_{to} and E_p showed significant differences between seasons in the same climatic variables. In general, both E_{to} and E_p were more sensitive to net radiation, followed by air temperature, relative humidity, and wind-speed; this was consistent for both periods, baseline and projected. The sensitivity coefficients could be used to obtain the accurate change in the atmospheric demand for water vapour. In terms of sensitivity coefficients, the E_p responded better to the changes in climatic variables than the E_{to} . Overall, the outcomes of this chapter can provide reference information to understand the implications of climate change for the future water balance in a Mediterranean environment and to improve the regional strategy for agricultural water management and irrigation practices.

References

- Agam N, Berliner PR, Zangvil A, Ben-Dor E (2004) Soil water evaporation during the dry season in an arid zone. *Journal of Geophysical Research: Atmospheres* 109:16103.
- Allen RG (2011) Skin layer evaporation to account for small precipitation events – An enhancement to the FAO-56 evaporation model. *Agricultural Water Management* 99(1):8–18.
- Allen RG, Smith M, Perrier A, Pereira LS (1994) An update for the definition of reference evapotranspiration. *ICID Bulletin* 43:92.
- Allen RG, Pereira LS, Raes D, Smith M (1998) *Crop evapotranspiration: Guidelines for computing crop water requirements*. Irrigation and Drainage paper No. 56. FAO, Rome.

- Ambas VTh, Baltas E (2012) Sensitivity analysis of different evapotranspiration methods using a new sensitivity coefficient. *Global NEST Journal* 14(3):335–343.
- Aydın M (2008) A model for evaporation and drainage investigations at ground of ordinary rainfed-areas. *Ecological Modelling* 217(1–2):148–156.
- Aydın M, Keçecioglu SF (2010) Sensitivity analysis of evaporation module of E-DiGOR model. *Turkish Journal of Agriculture and Forestry* 34(6):497–507.
- Aydın M, Yang SL, Kurt N, Yano T (2005) Test of a simple model for estimating evaporation from bare soils in different environments. *Ecological Modelling* 182:91–105.
- Aydın M, Yano T, Evrendilek F, Uygur V (2008) Implications of climate change for evaporation from bare soils in a Mediterranean environment. *Environmental Monitoring and Assessment* 140:123–130.
- Aydın M, Jung YS, Yang JE, Lee HI (2014) Long-term water balance of a bare soil with slope in Chuncheon, South Korea. *Turkish Journal of Agriculture and Forestry* 38:80–90.
- Aydın M, Jung YS, Yang JE, Kim SJ, Kim KD (2015) Sensitivity of soil evaporation and reference evapotranspiration to climatic variables in South Korea. *Turkish Journal of Agriculture and Forestry* 39:652–662.
- Bellot J, Chirino E (2013) Hydrobal: An eco-hydrological modelling approach for assessing water balances in different vegetation types in semi-arid areas. *Ecological Modelling* 266:30–41.
- Beven K (1979) A sensitivity analysis of the Penman–Monteith actual evapotranspiration estimates. *Journal of Hydrology* 44:169–190.
- Bittelli M, Ventura F, Campbell GS, Snyder RL, Gallegati F, Pisa PR (2008) Coupling of heat, water vapor, and liquid water fluxes to compute evaporation in bare soils. *Journal of Hydrology* 362(3–4):191–205.
- Brown RW, Oosterhuis DM (1992) Measuring plant and soil water potentials with thermocouple psychrometers: Some concerns. *Agronomy Journal* 84:78–86.
- Coleman G, DeCoursey DG (1976) Sensitivity and model variance analysis applied to some evaporation and evapotranspiration models. *Water Resources Research* 12(5):873–879.
- Dhungana P, Eskridge KM, Weiss A, Baenziger PS (2006) Designing crop technology for a future climate: An example using response surface methodology and the CERES-Wheat model. *Agricultural Systems* 87:63–79.
- Ebrahimipour M, Ghahreman N, Orang M (2014) Assessment of climate change impacts on reference evapotranspiration and simulation of daily weather data using SIMETAW. *Journal of Irrigation and Drainage Engineering* 140(2), Article No: 04013012.
- Estévez J, Gavilán P, Berengena J (2009) Sensitivity analysis of a Penman–Monteith type equation to estimate reference evapotranspiration in southern Spain. *Hydrological Processing* 23:3,342–3,353.
- Fujihara Y, Tanaka K, Watanabe T, Nagano T, Kojiri T (2008) Assessing the impacts of climate change on the water resources of the Seyhan River Basin in Turkey: Use of dynamically downscaled data for hydrologic simulations. *Journal of Hydrology* 353:33–48.
- Gao G, Xu CY, Chen D, Singh VP (2012) Spatial and temporal characteristics of actual evapotranspiration over Haihe River basin in China estimated by the complementary relationship and the Thornthwaite water balance model. *Stochastic Environmental Research and Risk Assessment* 26(5):655–669.
- Giorgi F, Lionello P (2008) Climate Change Projections for the Mediterranean Region. *Global Planet Change* 63:90–104.
- Gong L, Xu C, Chen D, Halldin S, Chen YD (2006) Sensitivity of the Penman–Monteith reference evapotranspiration to key climatic variables in the Changjiang (Yangtze River) basin. *Journal of Hydrology* 329:620–629.
- Goyal RK (2004) Sensitivity of evapotranspiration to global warming: A case study of arid zone of Rajasthan (India). *Agricultural Water Management* 69:1–11.
- Hernegger M, Nachtebel HP, Haiden T (2012) Evapotranspiration in high alpine catchments – an important part of the water balance. *Hydrological Research* 43(4):460–475.
- Huo Z, Dai X, Feng S, Kang S, Huang G (2013) Effect of climate change on reference evapotranspiration and aridity index in arid region of China. *Journal of Hydrology* 492:24–34.

- Hupet F, Vanclooster M (2001) Effect of the sampling frequency of meteorological variables on the estimation of the reference evapotranspiration. *Journal of Hydrology* 243:192–204.
- IPCC (2013) Summary for Policymakers. In Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press.
- Irmak S, Payero JO, Martin DL, Irmak A, Howell TA (2006) Sensitivity analyses and sensitivity coefficients of standardized daily ASCE Penman-Monteith equation. *Journal of Irrigation and Drainage Engineering* 132(6):564–578.
- Kimura F, Kitoh A (2007) *Downscaling by Pseudo Warming Method. Final Report of the ICCAP*, Research Institute for Humanity and Nature, Kyoto, Japan.
- Kitoh A, Hosaka M, Adachi Y, Kamiguchi K (2005) Future projections of precipitation characteristics in East Asia simulated by the MRI CGCM2. *Advances in Atmospheric Sciences* 22:467–478.
- Kwon, H, Choi M (2011) Error assessment of climate variables for FAO-56 reference evapotranspiration. *Meteorology and Atmospheric Physics* 112:81–90.
- Li ZL, Li ZJ, Xu ZX, Zhou X (2013) Temporal variations of reference evapotranspiration in Heihe River basin of China. *Hydrology Research* 44(5):904–916.
- McCuen RH (1974) A sensitivity and error analysis of procedures used for estimating evaporation. *Water Resources Bulletin* 10(3):486–498.
- Moratiel R, Duran JM, Snyder RL (2010) Responses of reference evapotranspiration to changes in atmospheric humidity and air temperature in Spain. *Climate Research* 44:27–40.
- Pockley P (2009) The evaporation paradox. *Australasian Science* Nov/Dec. 2009, 12–13.
- Rana G, Katerji N (1998) A measurement based sensitivity analysis of the Penman-Monteith actual evapotranspiration model for crops of different height and in contrasting water status. *Theoretical and Applied Climatology* 60:141–149.
- Roderick ML, Farquhar GD (2002) The cause of decreased pan evaporation over the past 50 years. *Science* 298:1410–1411.
- Roderick ML, Farquhar GD (2004) Changes in Australian pan evaporation from 1970 to 2002. *International Journal of Climatology* 24:1077–1090.
- Romano E, Giudici M (2009) On the use of meteorological data to assess the evaporation from a bare soil. *Journal of Hydrology* 372(1–4):30–40.
- Sanchez-Gomez E, Somot S, Mariotti A (2009) Future changes in the Mediterranean water budget projected by an ensemble of regional climate models. *Geophysical Research Letters* 36: L21401.
- Saxton KE (1975) Sensitivity analysis of the combination evapotranspiration equation. *Agricultural Meteorology* 15:343–353.
- Tabari H, Hosseinzadeh-Talaee P (2014) Sensitivity of evapotranspiration to climatic change in different climates. *Global Planet Change* 115:16–23.
- Tao F, Yokozawa M, Hayashi Y, Lin E (2003) Terrestrial water cycle and the impact of climate change. *Agriculture, Ecosystems and Environment* 95:203–215.
- Terink W, Immerzeel WW, Droogers P (2013) Climate change projections of precipitation and reference evapotranspiration for the Middle East and Northern Africa until 2050. *International Journal of Climatology* 33(14):3055–3072.
- US-NAS and Royal Society (2014) *Climate Change: Evidence and Causes* (An overview from the Royal Society and the US National Academy of Sciences. The primary writing team: Eric Wolff FRS, Inez Fung, Brian Hoskins FRS, John Mitchell FRS, Tim Palmer FRS, Benjamin Santer, John Shepherd FRS, Keith Shine FRS, Susan Solomon, Kevin Trenberth, John Walsh, Don Wuebbles).
- Vanderborght J, Graf A, Steenpass C, Scharnagl B, Prolingheuer N, Herbst M, Franssen HJH, Vereecken H (2010) Within-Field Variability of Bare Soil Evaporation Derived from Eddy Covariance Measurements. *Vadose Zone Journal* 9(4):943–954.

- Wallace JS, Jackson NA, Ong CK (1999) Modelling soil evaporation in an agroforestry system in Kenya. *Agricultural and Forest Meteorology* 94:189–202.
- Xiao X, Horton R, Sauer TJ, Heitman JL, Ren T (2011) Cumulative soil water evaporation as a function of depth and time. *Vadose Zone Journal* 10(3):1016–1022.
- Xie H, Zhu X (2013) Reference evapotranspiration trends and their sensitivity to climatic change on the Tibetan Plateau (1970–2009). *Hydrological Processes* 27(25):3685–3693.
- Xing W, Wang W, Shao Q, Peng S, Yu Z, Yong B, Taylor J (2014) Changes of reference evapotranspiration in the Haihe River Basin: Present observations and future projection from climatic variables through multi-model ensemble. *Global Planet Change* 115:1–15.
- Xu YP, Pal SL, Fu GT, Tian Y, Zhang XJ (2014) Future potential evapotranspiration changes and contribution analysis in Zhejiang Province, East China. *Journal of Geophysical Research: Atmospheres* 119(5):2,174–2,192.
- Yang XL, Ren LL, Singh VP, Liu XF, Yuan F, Jiang SH, Yong B (2012) Impacts of land use and land cover changes on evapotranspiration and runoff at Shalamulun River watershed, China. *Hydrological Research* 43(1–2):23–37.
- Yano T, Aydin M, Haraguchi T (2007) Impact of climate change on irrigation demand and crop growth in a Mediterranean environment of Turkey. *Sensors* 7(10):2297–2315.
- Yukimoto S, Noda A, Kitoh A, Sugi M, Kitamura Y, Hosaka M, Shibata K, Maeda S, Uchiyama T (2001) A new Meteorological Research Institute coupled GCM (MRI-CGCM2) – its climate and variability. *Papers in Meteorology and Geophysics* 51:47–88.
- Zhang XC, Liu WZ (2005) Simulating potential response of hydrology, soil erosion, and crop productivity to climate change in Changwu tableland region on the Loess Plateau of China. *Agricultural and Forest Meteorology* 131:127–142.
- Zhang Q, Xu CY, Chen XH (2011) Reference evapotranspiration changes in China: Natural processes or human influences? *Theoretical and Applied Climatology* 103(3–4):479–488.