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ORIGINAL PAPER

Actual evapotranspiration for a reference crop within measured and future changing climate periods in the Mediterranean region

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Abstract The study compares two formulas for calculating the daily evapotranspiration ET_0 for a reference crop. The first formula was proposed by Allen et al. (AL), while the second one was proposed by Katerji and Perrier with the addition of the carbon dioxide (CO_2) effect on evapotranspiration (KP). The study analyses the impact of the calculation by the two formulas on the irrigation requirement (IR). Both formulas are based on the Penman-Monteith equation but adopt different approaches for parameterising the canopy resistance r_c. In the AL formula, r_c is assumed constant and not sensitive to climate change, whereas in the KP formula, r_c is first parameterised as a function of climatic variables, then ET_0 is corrected for the air CO_2 concentration. The two formulas were compared in two periods. The first period involves data from two sites in the Mediterranean region within a measured climate change period (1981–2006) when all the input climatic variables were measured. The second period (2070–2100) involves data from a future climate change period at one site when the input climatic variables were forecasted for two future climate scenarios (A2 and B2). The annual cumulated values of ET_0 calculated by the AL formula are systematically lower than those determined by the KP formula. The differences between the ET_0 estimation with the AL and KP formulas have a strong impact on the determination of the IR for the reference crop. In fact, for the two periods, the annual values of IR when ET_0 is calculated by the AL formula are systematically lower than those calculated by the KP formula. For the actual measured climate change period, this reduction varied from 26 to 28 %, while for the future climate change period, it varied based on the scenario from 16 % (A2) to 20 % (B2).

1 Introduction

The crop water requirement, which can be considered as equivalent to the actual evapotranspiration (Perrier 1985), for a reference crop (ET_0) represents the processes of evaporation and transpiration from the vegetation surface. The reference crop should closely resemble an extensive surface of green grass or Alfalfa that is well watered, actively growing and completely shading the ground and that has an assumed uniform height of 0.12 m, an albedo of 0.23 and a fixed surface resistance equal to 70 s m^{-1}. The requirement that the crop surface should be extensive and uniform is based on the assumptions that all fluxes are horizontally uniform and directed upwards (Allen et al. 1998).

The irrigation requirement (IR) for a reference crop corresponds to the volume of water needed to compensate for the deficit between the values of ET_0 and the water supplied by precipitation (Jensen et al. 1990; Allen et al. 2007). The IR values of a reference crop are key agroclimatic data used to determine crop water requirement (Allen et al. 1998; Sakellariou-Makrantonaki and Vagenas 2006; Rodriguez-Diaz et al. 2007; Shen et al. 2013) and the hydrological cycle terms (Shiklomanov 2000; Kumar et al. 2002; Torres et al. 2011). Accurate estimation of IR is indispensable for different purposes: determination of irrigation scheduling, irrigation system design, water resources planning and management and prediction of impacts of climate change on crop

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productivity and irrigation need (Knox et al. 1997; Downing et al. 2003; Bruinsma 2003, 2009; de Fraiture and Wichelns 2010; Shahid 2011; Leflaive et al. 2012).

The daily ET_0 is rarely directly measured (see review by Rana and Katerji 2000). In practice, the daily ET_0 is often estimated using formulas proposed by different authors (e.g. Thornthwaite 1948; Penman 1948, 1956, 1963; Makking 1957; Turc 1961; Priestley and Taylor 1972; Hargreaves and Samani 1985; Allen et al. 1989, 1998). Following the theoretical analysis by Penman (1956); Monteith (1965); Thom (1972) and Perrier (1975), these formulas must take into account three groups of variables that are involved in the crop evapotranspiration process: climatic (available energy, air temperature and vapour pressure deficit), aerodynamic (air resistance r_a for water vapour) and biological (surface crop resistance r_c for water vapour). Among the above-mentioned formulas, the one proposed by Allen et al. (1998) in the FAO-56 publication is the most interesting. In fact, it is based on the theoretical work of Penman (1948, 1956) and Monteith (1965) that takes into consideration, albeit in simplified form, the variables previously identified. This is the reason because the Allen et al. (1998) ET_0 formula has been included in many models when the above-mentioned input variables are available, with the aim to simulate the irrigation scheduling and crop productivity for the measured (with "measured climate change" we mean the present climate) and forecasted future climate change periods (Bruinsma 2003, 2009; Hopmans and Maurer 2008; Brisson and Levrault 2010; Raes et al. 2009; Lhomme et al. 2009; Moratiel et al. 2010; Lovelli et al. 2010; Hoogenboom et al. 2010; Zhi et al. 2012; Campi et al. 2012; Palumbo et al. 2012; Leflaive et al. 2012). The results of the simulations obtained using these models can concern different time scales, with annual or multiannual observations (Katerji et al. 2010; Shen et al. 2013) up to the present-future transition, 2030, 2050 or 2080 (Bruinsma 2003, 2009; Fischer et al. 2007; Giannakopoulos et al. 2009), as well as different space scales, plot scales (Brisson et al. 2003; Gusev and Nasonova 2003; Steduto et al. 2009; DeJonge et al. 2012; Campi et al. 2012; Palumbo et al. 2012), basin scales (Giannakopoulos et al. 2009; Lovelli et al. 2010; Brisson and Levrault 2010; Moratiel et al. 2011; Shen et al. 2013) and continental and planetary scales (Bruinsma 2003, 2009; Fischer et al. 2007; Leflaive et al. 2012). Finally, when the input variables in the Allen et al. (1998) formula are not available, this formula is used as a reference method to validate simpler formulas for calculating ET_0 with a smaller number of variables for both previously mentioned measured and forecasted future climate change periods (Jabloun and Sahli 2008; Espadafor et al. 2011; Palumbo et al. 2012).

The adoption of the Allen et al. (1998) ET_0 formula as an input variable or as a reference method in the previous studies is aimed to obtain reliable ET_0 values under climate change conditions, involving different climatic variables: precipitation, air temperature and vapour pressure deficit and air carbon dioxide (CO_2) concentration (IPCC 2007). As a consequence, the robustness of the IR values and the credibility of the proposed water management methods following these studies depend on the reliability attributed to this last hypothesis, i.e. the reliability of the Allen et al. (1998) ET_0 formula. However, the actual reliability of this ET_0 formula has not been adequately demonstrated, considering the criticisms attributed to it by several subsequent studies, particularly some studies conducted in the Mediterranean region. For example, Katerji and Rana (2006, 2011, 2014) noted that the Allen et al. (1998) formula was calibrated uniquely for an irrigated grass having a crop stomatal resistance r_c equal to 70 s m^{-1}. Furthermore, this value is considered to be constant during the day and for any type of climate (humid, arid or semi-arid) and indifferent to the climate change. However, this hypothesis contradicts the reports in the literature that have analysed the variation of stomatal resistance with the following climatic variables: available energy (A), air temperature (T_a), air vapour pressure deficit (D), wind speed (u) and air CO_2 concentration (see for example, Long et al. 2004; Damour et al. 2010; for an extensive and recent review). In particular, this hypothesis was not verified in the experimental trials performed in the Mediterranean region on irrigated grass surfaces. In fact, these experiments revealed significant variations in the canopy resistance r_c on daily and seasonal scales in relation to the previously identified climatic variables (Choisnel et al. 1992; Rana et al. 1994; Calvet et al. 1998; Todorovic 1999; Steduto et al. 2003; Lecina et al. 2003; Rana and Katerji 1998, 2006; Perez et al. 2006). Furthermore, after a comparison conducted in southern Italy over 840 days, Rana et al. (1994) noticed that the Allen et al. (1989) formula underestimated the calculated ET_0 by approximately 18 %, with respect to the ET_0 measured daily with a weighing lysimeter.

Following a quite recent theoretical analysis of the Allen et al. (1998) formula, Shuttleworth and Wallace (2009) concluded that its poor performance in a semi-arid region can be predicted because the humid conditions are an implicit prerequisite in this formula, which rarely occurs in this region. The Mediterranean region can be considered as one of the most vulnerable to water scarcity in future climate change projections (Giorgi and Lionello 2008; Espadafor et al. 2011). Furthermore, other studies (Campi et al. 2009; De Luis et al. 2009; Gonzalez-Hidalgo et al. 2009; Palumbo et al. 2009) have confirmed the current changes in climate characteristics in this region during the second half of the twentieth century.

The present study compares the performance of two formulas to determine the ET_0 in the Apulia region in southern Italy: the formula (AL), proposed by Allen et al. (1998) and the formula (KP) proposed by Katerji and Perrier (1983). KP formula takes into account the links between crop resistance r_c and the climatic variables by combining the analysis performed in two previous studies. The first analysis (Katerji and Perrier 1983) takes into consideration the role of some climatic variables, including A, D, T_a and u on the resistance r_c of irrigated grass. The second analysis (Olioso et al. 2010) takes into account the role of the CO_2 air concentration in increasing the daily values of ET_0.

The comparison performed between the two formulas for calculating ET_0 will concern two periods:

- The first period, which is within present actual changing climate period, concerns the 1981–2006 period. The calculation obtained by the two formulas will be based on measured input variables.
- The second period, which is during a future climate change period, concerns the 2070–2100 period. The calculation will be based on the input climatic variables forecasted by the HadCH3 model for two future climate scenarios, A2 and B2, according to the procedure described by Hulme et al. (2002).

The main objective of the present study is to provide answers to the following questions:

- When the above-mentioned two formulas are used to calculate ET_0 within actual measured changing climate period in a Mediterranean region, is it possible to observe significant divergences between the tested formulas? For which climatic conditions do the divergences become significant? Finally, which formula better simulates the direct weighing lysimeter-measured ET_0?
- When the same formulas are applied for ET_0 calculations of future climate change scenarios, are the previous divergences observed? How do they evolve?
- What are the impacts of the ET_0 calculation by the two formulas on the irrigation requirement, IR, values for a reference crop determined for measured and forecasted future climate change periods?

2 Theoretical bases of the tested formulas

The Allen et al. (1998) (AL formula) is based on the Penman-Monteith (PM) equation for calculating the daily-scale ET_0 values and was originally formulated for annual crops (Monteith 1965). The PM equation is valid on a time scale from a few minutes to 1 h and for large enough surfaces for which advection effects can be neglected (Perrier 1975; Brutsaert 1982; Stull 1988). In the PM equation, the actual crop evapotranspiration as latent heat flux (λET in W m^{-2}) is written as follows:

$$\lambda ET = \frac{\Delta A + \rho c_p D / r_a}{\Delta + \gamma (1 + r_c / r_a)} \tag{1}$$

where $A = R_n - G$ is the available energy in W m^{-2}, with R_n net radiation and G soil heat flux. ρ is the air density in kg m^{-3}. Δ is the slope of the saturation pressure deficit versus temperature function in kPa °C^{-1}. γ is the psychrometric constant in kPa °C^{-1}. c_p is the specific heat of moist air in J kg^{-1} °C^{-1}. D is the vapour pressure deficit of the air in kPa. r_c is the bulk canopy resistance in s m^{-1}. r_a is the aerodynamic resistance in s m^{-1}, and λ is the latent heat of evaporation in J kg^{-1}.

In the AL formula, the resistance r_a of the reference surface is modelled as:

$$r_a = \frac{208}{u_z} \tag{2}$$

where u_z is the wind speed measured 2 m above the surface. While the resistance r_c of the reference surface is considered as constant during the day and equal to 70 s m^{-1} (Allen et al. 1989, 1998) and not affected by climate changes.

By introducing into Eq. (1) the values of r_a (Eq. 2) and constant value of r_c (70 s m^{-1}), the formulation of ET_0, for an irrigated grass surface, on a daily scale (mm d^{-1}), can be written by the AL formula as

$$ET_0 = \frac{0.408 A + \gamma \frac{900}{T_a + 273} u_2 D}{\Delta + \gamma (1 + 0.34 u_2)} \tag{3}$$

It only requires the measurement of the four weather variables A, D, u and T_a.

The Katerji and Perrier (1983) model (KP formula) also based their analysis of actual evapotranspiration, ET, on the PM equation at the hourly scale to meet the permanent regime requirements. However, they modified the calculation of the resistance, r_a, and, furthermore, proposed a specific procedure for parameterising r_c as a function of the climatic variables. Perrier (1975) proposed calculating the resistance, r_a, between the top of the crop and a reference point (z) located in the boundary layer above the canopy as follows:

$$r_a(z) = \frac{\ln\left(\frac{z-d}{z_0}\right) \ln\left(\frac{z-d}{h_c-d}\right)}{k^2 u_z} \tag{4}$$

For a grass crop having height (h_c) 0.12 m, the variables d (displacement height) and z_0 (roughness length) have constant values. Thus, the resistance, r_a, has as input only the value of the wind speed measured 2 m above the surface, since k is the von Kármán constant.

Contrary to AL formula Katerji and Perrier (1983) considered the canopy resistance as variable, they proposed to calculate r_c with the following relation:

$$\frac{r_c}{r_a} = a \frac{r^*}{r_a} + b \tag{5}$$

r^* ($\mathrm{s\,m^{-1}}$) is called critical resistance and is modelled by the following relation:

$$r^* = \frac{\Delta + \gamma}{\Delta\gamma} \frac{\rho c_p D}{A} \tag{6}$$

The values of the a and b coefficients in Eq. (5) are specific for each crop species (see Katerji and Rana 2014 for a review, including reference crops).

At hourly scale (ET, $\mathrm{mm\,h^{-1}}$), by combining equations (1) and (5), the KP formula becomes

$$\mathrm{ET} = \frac{1}{\lambda} \frac{\Delta \mathrm{A} + \rho c_p D / r_a}{\Delta + \gamma\left(a\frac{r^*}{r_a} + b + 1\right)} \tag{7}$$

The calculation of the ET on a daily time scale in $\mathrm{mm\,d^{-1}}$ should be obtained by summing the hourly values determined by Eq. (7) (Katerji and Rana 2006). When this solution is not possible, which is precisely the case for future climate forecasts when only daily values of the climatic variables are available, it is necessary to adapt formula (7) to the daily scale, as detailed in the following.

On the daily scale, the KP formula of actual evapotranspiration can be written as follows (Katerji and Perrier 1983):

$$\mathrm{ET} = \frac{1}{\lambda} C_d \frac{\Delta}{\Delta + \gamma} A_d \tag{8}$$

where A_d is the daily value of the available energy A, and C_d is the daily coefficient expressed by the following:

$$C_d = \frac{1 + \frac{\gamma}{\gamma + \Delta}\left(\frac{r^*}{r_a}\right)_d}{1 + \frac{\gamma}{\gamma + \Delta}\left(\frac{r_c}{r_a}\right)_d} \tag{9}$$

Using experimental tests conducted on irrigated alfalfa crop (Katerji and Perrier 1983) and irrigated grass (Rana et al. 1994), these authors demonstrated that it is possible to describe the variation of the coefficient C_d on a daily scale as a function of the climatic variables using the following relation:

$$C_d = \alpha\left(\frac{r^*}{r_a}\right)_d + \beta \tag{10}$$

where $(r^*/r_a)_d$ is the daily value of the ratio (r^*/r_a) obtained by introducing the four climatic variables on a daily scale (A, D, u and T_a) in the equations (4) and (6).

Finally, the introduction of the α and β coefficient values, as calibrated for the irrigated grass in Eq. (10), now permits adaptation of the general Eq. (8) to the determination of daily reference evapotranspiration $\mathrm{ET_0}$. For practical purposes, this determination requires, as does the AL formula, the determination on a daily scale of the same climatic variables: A, D, u and T_a.

The previous formula (Eq. 8) takes into accounts only four climatic variables affecting r_c. However, this formula still does not take into account the impact of the air $\mathrm{CO_2}$ concentration value on the resistance r_c.

Increases in the air $\mathrm{CO_2}$ concentration induces, with very few exceptions (Bernacchi et al. 2007), increases in the leaf stomatal resistance of most studied crop species (Long et al. 2004; Ainsworth and Long 2005), including grass (Calvet et al. 1998), and decreases in the water consumed by the crops during the growth cycle (Hunsaker et al. 2000; Bethenod et al. 2001). Unfortunately, the air $\mathrm{CO_2}$ concentration is still not a standard climatic variable determined routinely at any location on hourly or daily scales like the other climatic variables. On the basis of the mechanistic relationships between the stomatal resistance and air $\mathrm{CO_2}$ concentration determined for irrigated grass by Calvet et al. (1998), Olioso et al. (2010) proposed the use of the factor F to correct the daily values of calculated $\mathrm{ET_0}$ to take into account the effects of $\mathrm{CO_2}$ increases on water vapour exchanges between crop and atmosphere. Therefore, by taking into account factor F, Eq. (8) becomes

$$\mathrm{ET_{0[CO_2]}} = F \times \mathrm{ET_{0[370ppm]}} \tag{11}$$

where $\mathrm{ET_{0[CO2]}}$ is the $\mathrm{ET_0}$ under a given air $\mathrm{CO_2}$ concentration value; $\mathrm{ET_{0[370ppm]}}$ is the daily $\mathrm{ET_0}$ calculated for an air $\mathrm{CO_2}$ concentration value of 370 ppm (the actual one); F is the correction factor linked to the air $\mathrm{CO_2}$ concentration in ppm according to the following relationship:

$$F = 1.1403 - 3.8979 \times 10^{-4} \times [\mathrm{CO_2}] \tag{12}$$

The value of F is approximately 1 when the mean annual value of the air $\mathrm{CO_2}$ concentration is equal to 370 ppm. F decreases or increases when the $\mathrm{CO_2}$ concentration is higher or lower than this threshold. For example, the decrease is approximately 7.5 and 13 % when the $\mathrm{CO_2}$ concentration reaches 550 and 700 ppm, respectively.

By combining Eqs. (8) and (12), the KP formula for determining daily-scale ($\mathrm{mm\,d^{-1}}$) $\mathrm{ET_0}$ under a varied range of air $\mathrm{CO_2}$ concentrations is as follows:

$$\mathrm{ET_{0[CO_2]}} = F \times \frac{1}{\lambda} C_d \frac{\Delta}{\Delta + \gamma} A_d \tag{13}$$

The correction factor F is calculated from the mean annual values of the air $\mathrm{CO_2}$ concentration in ppm. Actually, the forecast models of the future climate give $\mathrm{CO_2}$ concentration values only on that time scale.

It should be noted that the KP formula takes into account all the climatic variables (A, D, T_a, u and $\mathrm{CO_2}$ concentration) that are subject to change.

3 Methodology

3.1 The study area and the datasets

The trials were conducted in the Apulia region in southern Italy on two reference grass fields equipped with two meteorological stations that are managed by the Italian “Consiglio per la Ricerca in Agricoltura e l’analisi dell’Economia Agraria (CREA)”—“Research Unit for Cropping Systems in Dry Environments”:

- The first site is in Rutigliano (lat. 40° 59′ 33″ N, long. 17° 01′ 58″ E, 146 m a.s.l.). This site has provided climatic observations since 1981. In the reference field grass, a weighing lysimeter has been installed to directly measure the ET_0, which is indispensable in the present study to test and validate the two formulas used to calculate ET_0.
- The second site is in Foggia (lat. 41° 25′ 55″ N, long. 15° 31′ 35″ E, 86 m a.s.l.), which is approximately 130 km far from the first station (Fig. 1). It has supplied climatic variable data without interruption since 1950 for precipitation and since 1960 for all climatic variables. This long time series is indispensable for the present study, at first for analysing the evolution of the climatic variables during the second half of the twentieth century and then for using as weather inputs to create the future climate scenarios in the period 2070–2100.

The determination of the ET_0 and IR values in Rutigliano and Foggia during the same time period (1981–2006) is surely an advantage because it provides further information about the space variability affecting the calculations in the same region.

Quality control and gap filling of the measured climatic variables data were undertaken using the procedures proposed by Zhang and Yang (2004) and Vitale et al. (2010) and implemented with the *R* software package module *RClimDex*.

The tests to validate the AL and KP formulas (see Eqs. (3) and (13), respectively) were based on the data acquired during the period 1981–2006 on the Rutigliano site.

To evaluate the performances of the models, the slope and the coefficient of determination (r^2) of the linear regression between observed (O) and predicted (P) values were performed. Furthermore, the plot of O vs. model residuals is analysed for each model and the index of agreement (AI) was also used to assess the performances of the models, as following (Willmott 1981):

$$AI = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} \left(\left| P_i - \overline{O} \right| + \left| O_i - \overline{O} \right| \right)^2} \tag{14}$$

AI reflects the degree of agreement between observed and predicted values and varies from 0 (poor model) to 1 (perfect model).

3.2 The climate during the period 1981–2006

The Apulia region in southern Italy is subjected to a Mediterranean climate characterized by a cold and humid winter followed by a hot and dry summer. The mean daily air temperature measured in the winter (December–February) is approximately 8 °C, whereas the mean daily air temperature measured in the summer (June–September) is approximately 24 °C, but the maximum temperature during this season can reach 42 °C. Precipitation is not equally distributed throughout the year. In fact, 70 % of the annual precipitation falls

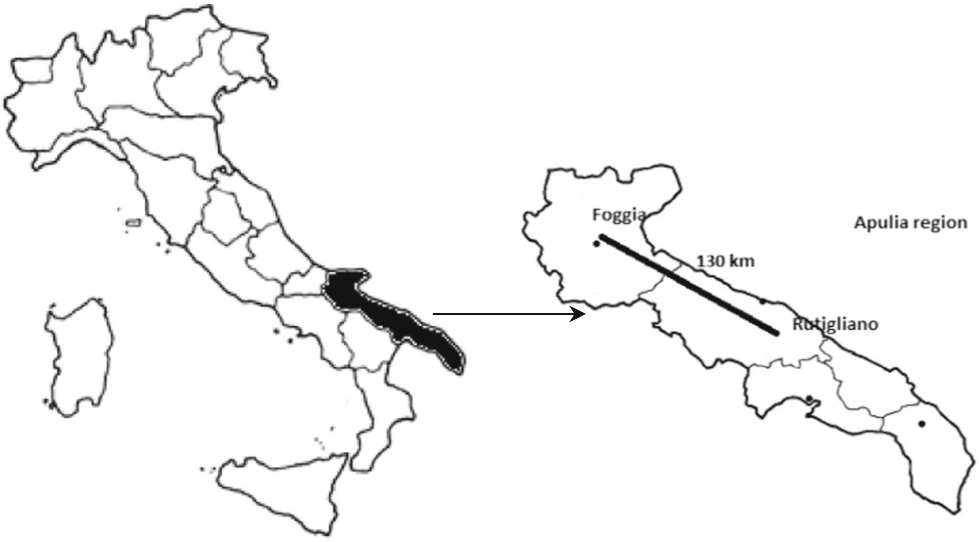


Fig. 1 Localization of the Apulia region on the map of Italy and the localization of the experimental sites of Foggia and Rutigliano in the region

during the months October–April (Palumbo et al. 2009; Vitale et al. 2010). Therefore, crop irrigation during spring-summer is indispensable in the Apulia region (Palumbo et al. 2009; Campi et al. 2012).

An analysis of the measured annual precipitation values and the minimum and maximum air temperatures at the Foggia site revealed a “break point” in approximately 1972 for precipitation and approximately 1981 for the minimal and maximal air temperatures (Fig. 2). Starting in 1972, the average annual precipitation significantly decreased by 168 mm compared with the previous period (468 mm/year instead of 636 mm/year), whereas year-to-year precipitation variability became more significant than that registered during the 1951–1972 period. Other authors (Werner et al. 2000; Auer et al. 2001; Brunetti et al. 2001; Lloyd-Hughes and Saunders 2002; Lana et al. 2003) came to the same conclusions starting from the analysis of the precipitation patterns observed in other localities of the Mediterranean and in other regions. Starting in 1981, the average annual minimal and maximal temperatures increase significantly by 0.8 and 1.1 °C, respectively. Similar results were found for Italy by Maugieri and Nanni (1998), Brunetti et al. (2006), Ciccarelli et al. (2008) and Toreti and Desiato (2008a, b).

For air CO_2, the Meteorological Service of the Italian Military Aeronautic (IAM) has regularly measured the CO_2 concentration in the air in the centre of Italy (Mt. Cimone 44° 11′ N, 10° 42′ E, 2165 m a.s.l.) since 1979. In Fig. 3, these data are presented for the period 1981–2006. Apadula et al. (2005) found that these CO_2 concentration values are very similar and convergent with those measured in northern Italy (Plateau Rosa, 45.93° N, 7.70° E, 3480 m a.s.l.) and in southern Italy (Lampedusa 35.5° N, 12.6° E, 45 m a.s.l.) by IAM. These

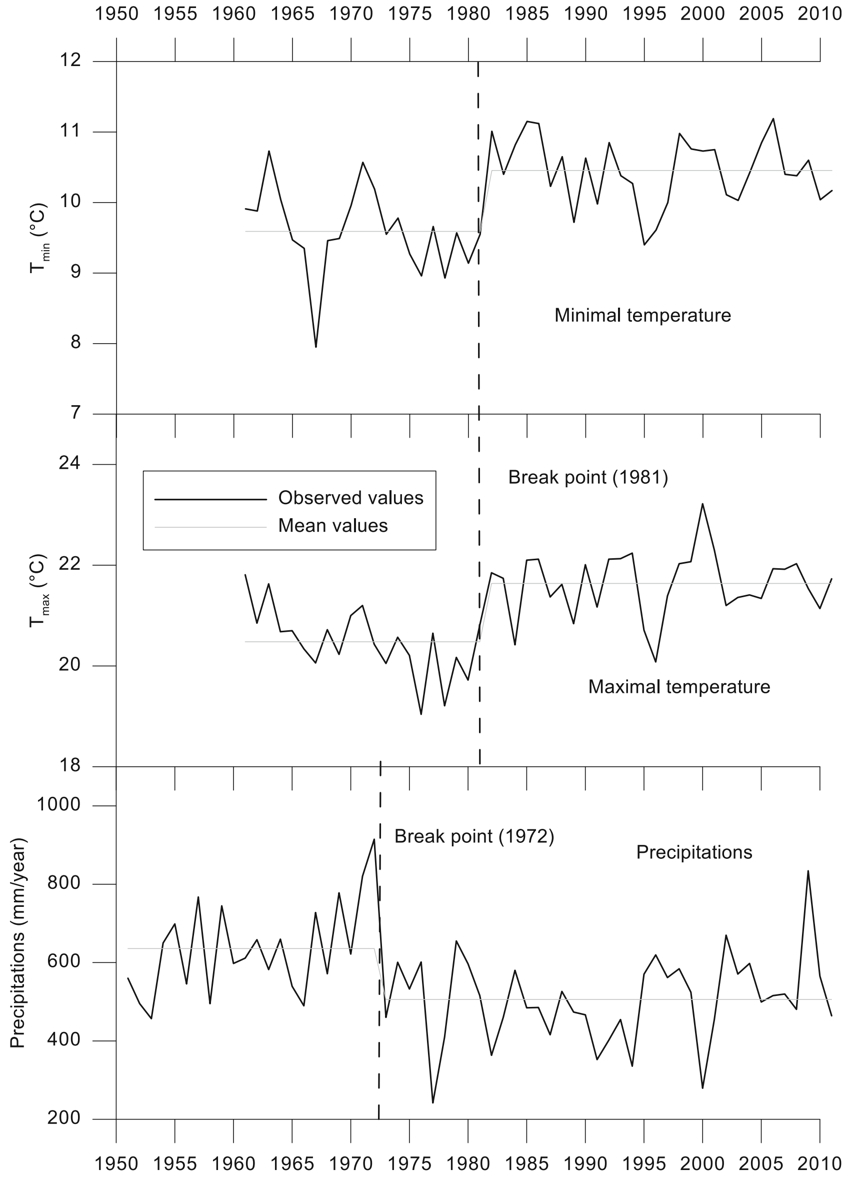


Fig. 2 Measured annual values of precipitation during 1951–2010 in Foggia site and measured annual values of minimal and maximal air temperatures in some site during 1961–2010. The mean values are indicated before and after the break point

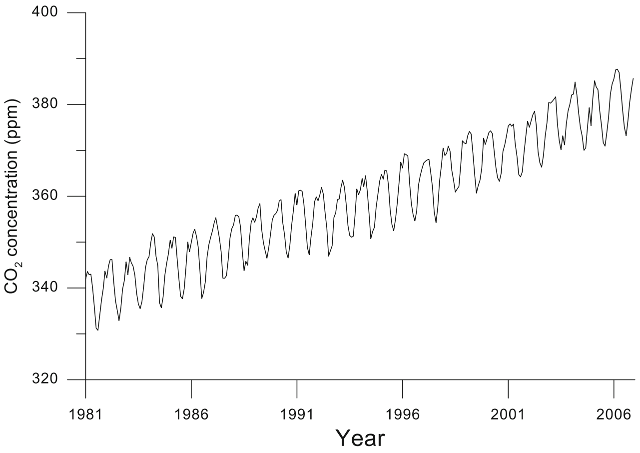


Fig. 3 Monthly values of air CO_2 concentration measured in Mt. Cimone (44° 11′ N, 10° 42′ E, 2165 m a.s.l., center Italy) during 1981–2006 period (after Apadula et al. 2005)

measurements highlight variations of approximately 10 ppm between the winter and the summer of each year. The highest CO_2 concentration values, which observed in winter, are well known to correspond to the energy supplied by fossil combustion during this season (Tans et al. 1989). Furthermore, the mean values of annual CO_2 concentration during the period 1981–2006 constantly and regularly increased by approximately 12 % (from 335 to 380 ppm).

Finally, other studies conducted in the Apulia region (Palumbo et al. 2009; Campi et al. 2012) have underlined the links between the climate change described above and the increase in the amounts of water required for irrigation of the main crops (tomato, olive trees and vineyards) of the region starting in the 1970s.

3.3 The climate forecast in the period 2070–2100

In this study, the weather data forecast for the Foggia site in the period 2070–2100 was derived from the third simulation of the Hadley Centre Global Circulation Model, HadCM3, from the regionalised dataset for the Europe HadRM3 (Hulme et al. 2002). Data were taken exclusively from the dataset provided at a 5-km grid resolution, almost centred on the meteorological station located in the experimental farm in Foggia for baseline of the 1961–1990 data. The Intergovernmental Panel on Climate Change (IPCC 2000, 2007) has published four emissions scenarios (A1, A2, B1 and B2) for use in climate change studies. For this study, two scenarios were used: the A2 (Business as usual, with air CO_2 concentration equal to 850 ppm in the 2100) and B2 scenarios (Environmental stewardship, with air CO_2 concentration equal to 600 ppm in the 2100). The variables forecasted by the HadRM3 model at the daily scale are temperature, precipitation, solar radiation, wind speed and relative humidity. The value for CO_2 is taken at an annual scale. This dataset does not contain ET_0 values. Therefore, the determination of ET_0 was performed using the AL and KP formulas according to the procedure described in the following section.

In Fig. 4, the forecasted annual mean values for the A2 and B2 scenarios of the minimum (4a) and maximum (4b) air temperature, the precipitation (4c) and the CO_2 air concentration (4d) are reported for the 2070–2100 period. The mean annual values of each previous variable during the 1981–2006 and 2070–2100 periods are also presented in the same figures. For both scenarios, the annual minimum and maximum air temperatures display a trend toward greater increases during the 2070–2100 period than during the 1981–2006 period. These trends are particularly important in the case of the maximum temperature (Fig. 4b). For this variable, the annual mean during the period 2070–2100 will increase by 8 and 5 °C, instead of 4 and 1 °C for the minimal temperature (Fig. 4a), following the given scenario (A2 or B2, respectively). For precipitation, the tendency in the 2070–2100 period is toward strong decreases with respect to the measured values during the 1981–2006 period (Fig. 4c). The forecasted reductions during the period 2070–2100 will be, following the given scenario (B2 and A2), between 33 and 47 % with respect to that measured during the period 1981–2006.

For both scenarios, the annual CO_2 concentration of the air (Fig. 4d) will increase according to the trend observed during the 1981–2006 period to reach 850 (A2) and 600 (B2) ppm in the year 2100.

In summary, all climatic scenarios strongly confirmed the tendency observed experimentally during the 1981–2006 period in regards to the increase in the annual air temperature and air CO_2 concentration and the decrease in annual precipitation.

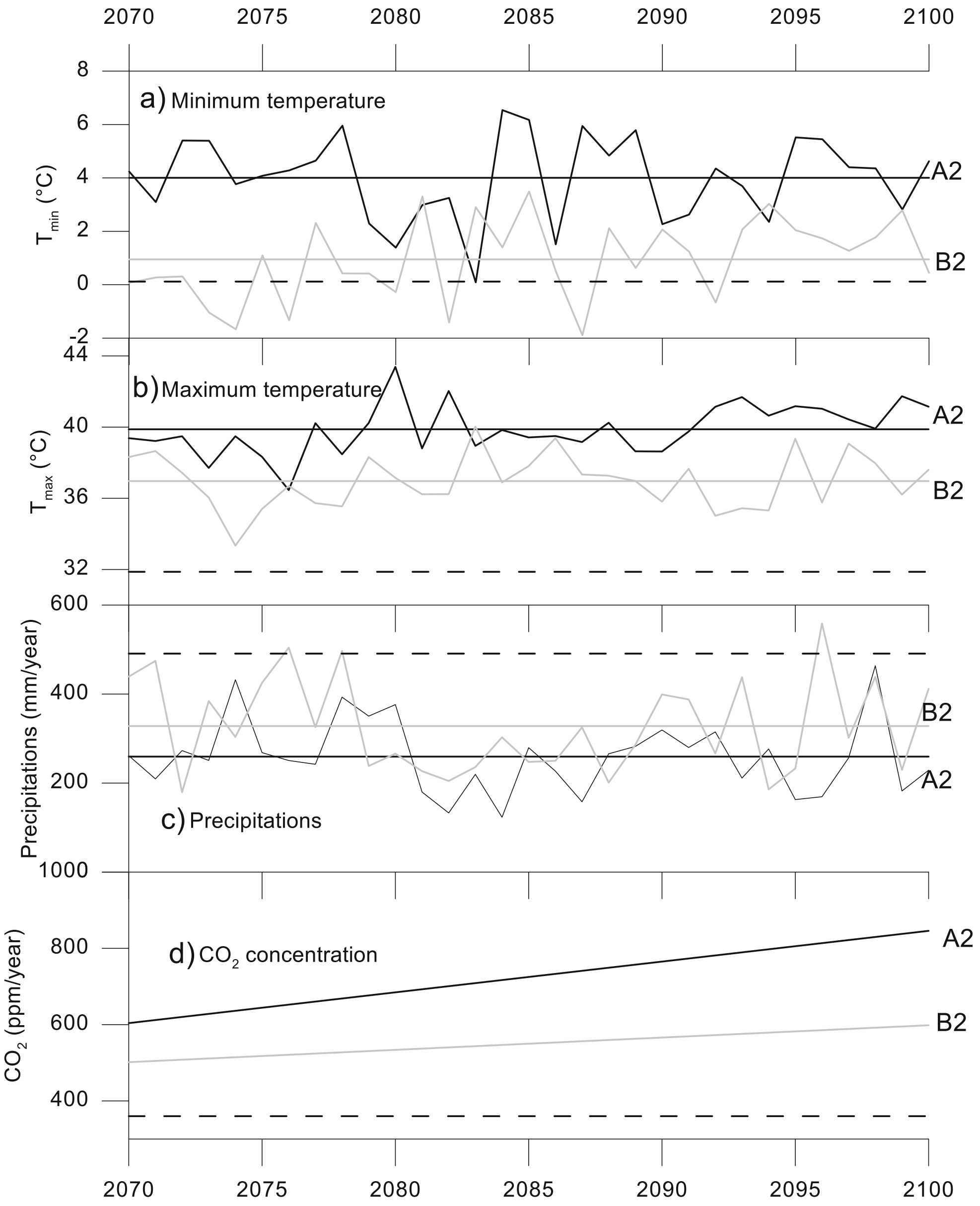
For the period 2070–2100, the daily values of global radiation (R_g), D, T_a and u and the annual values of the air CO_2 concentration were forecast.

3.4 Direct measurement and estimation of ET_0 at the daily scale in the period 1981–2006

3.4.1 Direct measurement with weighing lysimeters

This determination was conducted only at the Rutigliano site. In fact, a weighing lysimeter is installed at the site very close to the weather station in a 1-ha reference grass field. The equipment has a surface area of 4 m^2 and a resolution of 0.06 mm. The lysimeter is on a balance for measuring the mass variations due to the actual ET of the grass. This variation is converted into an electric signal and transmitted toward the data logger, which acquires the data continuously every 10 s and stores the hourly, daily and weekly means. A negative daily variation of weight corresponds to a daily value of ET_0, whereas a daily positive variation corresponds to a value of daily precipitation or water supplied by irrigation.

Fig. 4 Annual values of minimum (*a*) and maximum (*b*) air temperature, precipitation (*c*) and CO2 air concentration (*d*) forecasted by two scenarios A2 and B2 of future climate during 2070–2100 period. The mean values during the same period for each future climate scenarios are also indicated in figures *a*, *b* and *c*. The *dashed line* corresponds to the mean values within climate change (1981–2006) for each variable



3.4.2 ET_0 calculation using the AL and KP formulas

As for the analysis presented in Section 2, the ET_0 calculation using the AL and KP formulas requires the determination of four climatic variables on the daily scale, A, D, T_a and u, which are common to both the AL and KP formulas, and one variable, air CO_2 concentration, that is specific to the KP formula. Moreover, we recall that the daily KP formula needs a preliminary calibration to determine the α and β coefficients specific to the grass crop (see Eq. 10). For the period 1985–2006, all the input climatic variables were measured at the meteorological stations at Foggia and Rutigliano using the following procedure:

- The daily 24-h averages of D, T_a and u were usually measured directly by the stations using a standard setup 2 m above the soil surface. T_a and D were measured with a thermo-hygrometer (M100 Rotronic, USA), and u was measured using an anemometer (A100, Vector Ins., USA).
- The daily value of A (R_n-G) was calculated according to the recommendations by Katerji and Perrier (1983) during the day light periods from R_g values that were measured directly during the same period with a precision pyranometer (PSP Eppley, Newport, RI, USA) installed 2 m above the soil surface in the meteorological station. An experimental comparison conducted for the Rutigliano site during daylight periods of 210 days during 2012 and 2013 between the R_g values measured at the meteorological station and the (R_n-G = A) values measured on the irrigated grass at the same station led to the

following relationship: $A = 0.52\ R_g$ with $r^2 = 0.97$. This experimental relationship is considered a constant in this study for both sites for the measured and forecasted future climate change scenarios. The values of the air CO_2 concentration on a monthly scale were determined from the experimental data acquired in the centre of Italy (data at http://ds.data.jma.go.jp/gmd/wdcgg/).

3.4.3 Calibration of the coefficients α and β in the KP formula

The determination of the coefficients α and β specific for the grass crop was performed by analysing the daily linear relationship between the coefficient C_d and the ratio $(r^*/r_a)_d$ (see Eq. 10) during 14 clear days randomly chosen during June 2001. In practice, the daily coefficient C_d was calculated (see Eq. 8) during these days with daily ET_0 values, as measured using a lysimeter, and A_d values were calculated on a diurnal scale by R_g measurement. The ratio $(r^*/r_a)_d$ was determined (see Eqs. 4 and 6) by A_d values calculated on a diurnal scale, and D, T_a and u values were determined on a 24-h time scale. Figure 5 shows the relationship observed between C_d and $(r^*/r_a)_d$, as well as the determined coefficients α and β. The values of these coefficients were considered constant for the tests performed for the measured climate change data period and forecasted future climate change period.

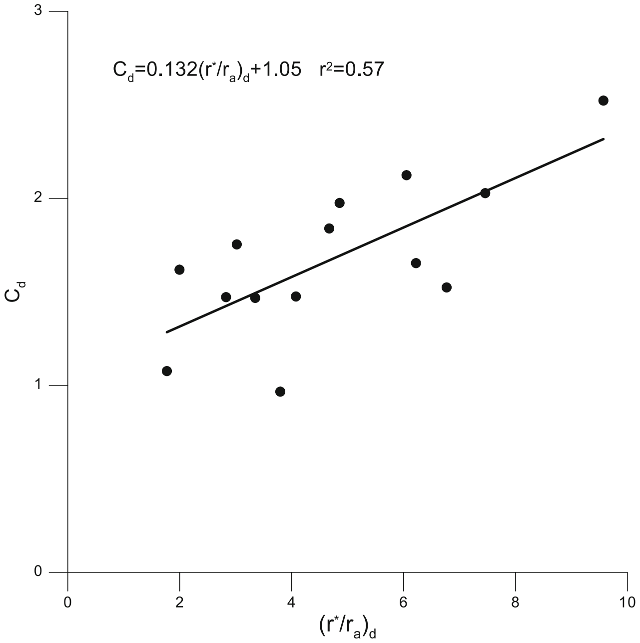


Fig. 5 Relation observed at daily scale on irrigated grass during 14 days in summer 2001 between C_d and the ratio $(r^*/r_a)_d$. r^* and r_a are climatic and aerodynamic resistance, respectively

3.5 Determination of irrigation requirement IR

In this study, a monthly and annual time step was used to determine the IR values from rainfall and ET_0 values, as determined using the AL or KP formula for the Rutigliano and Foggia sites, for the measured climate change data period and for the forecasted future climate change period. The monthly value of IR_i is calculated using the following equation:

$$IR_i = ET_{0,i} - P_i \tag{15}$$

where IR_i is the irrigation requirement of month i, in mm; $ET_{0,i}$ is the reference evapotranspiration of month i, in mm; and P_i is the precipitation of month i, in mm.

The annual value of IR is calculated from the cumulative monthly value of $ET_{0,i}$ and P_i between January and December.

4 Results and discussion

4.1 ET_0 calculated with the AL and KP formulas for the measured climate change period and impact on IR determination

Figure 6 shows mean monthly values of the measured precipitation and ET_0 on a monthly scale calculated using the AL (Eq. 3) and KP (Eq. 13) formulas for the measured climate change period (1981–2006) for the Foggia (Fig. 6a) and Rutigliano (Fig. 6b) sites. The following points are observed for both sites:

- The values of ET_0 are very close for both formulas during the 4 months (November–February) corresponding to the autumn and winter seasons in the Mediterranean region.
- During the other months of the year (March–October), corresponding to the spring and summer seasons in the Mediterranean region, the ET_0 calculated by the KP formula is higher than that calculated by the AL formula. In the case of the Foggia site, the observed differences between the formulas become significant between April and September.

-The ET_0 values calculated by the two formulas are not significantly different from the measured precipitation values for six (October–March in the Rutigliano site) to four (November–February in the Foggia site) months.

-For the other months of the year, between March or April and September or October, the values of ET_0 are significantly higher than those of the precipitation values for both formulas. Thus, the grass crop irrigation season is concentrated principally in the spring and summer seasons.

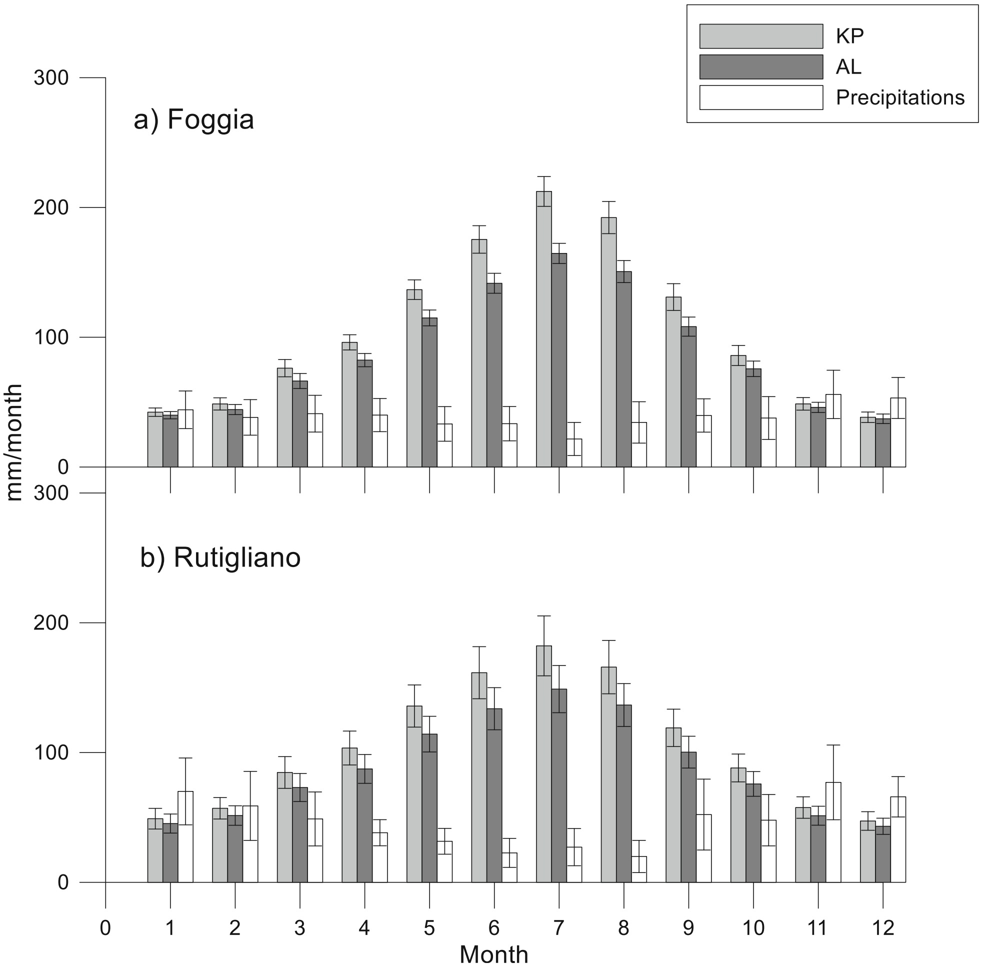


Fig. 6 Mean monthly values during measured climate change period during 1981–2006 of measured precipitation, calculated values by AL and KP-O formulas of reference evapotranspiration ET_0 and standard errors for two sites: Foggia (**a**) and Rutigliano (**b**)

On a yearly scale (Table 1), the annual values of ET_0, i.e. the annual values of water requirement for the reference crop, obtained by the KP formula were always significantly higher than those obtained by the AL formula for the same site. Moreover, Table 1 shows the mean annual value of the irrigation requirement, IR, for the reference crop at the Rutigliano and Foggia sites for the measured climate change period (1981–2006). The differences in the annual values of IR following the adopted formula to calculate ET_0 can range from 26 to 28 % for the Foggia and Rutigliano sites, respectively. The lower summed annual values of IR correspond to the ET_0 values calculated by the AL formula.

Table 1 Mean annual cumulated values in measured climate change during 1981–2006 period of reference evapotranspiration ET_0, precipitation P and irrigation requirement for reference crop (IR) together with standards error for two sites: Rutigliano and Foggia. KP is Katerji and Perrier (1983) model. AL is Allen et al. (1998) model

1981–2006		ET_0	Err.st (ET_0)	*P*	Err.st (*P*)	IR	Err.st (IR)
Rutigliano	KP	1248	36	560	31	689	61
	AL	1059	32			499	58
Foggia	KP	1333	24	491	23	842	42
	AL	1113	19			622	37

Figure 7 shows a comparison between the ET_0 values calculated by the KP (Fig. 7a) and AL (Fig. 7b) formulas and those measured by a lysimeter at the Rutigliano site on a daily scale precisely for the months May–August for four successive years (2000 to 2004). The slope of the linear regression between the measured and calculated ET_0 values is closer to 1 when the KP formula is used to calculate ET_0 than AL one. Nevertheless, the determination coefficients were not similar for the two approaches. The KP formula better forecast the ET_0 directly measured by lysimeter than the AL formula during the summer season for the measured climate change period (1986–2006). To complete the analysis of the performances of the models, on the right of each comparison (Fig. 7) between observed and modelled values, also, the plot of observed values vs model residuals is shown for models AL and KP. These plots stress the better performances of model KP (there is no pattern of residuals in function of the observed values) with respect to the AL model (a clear linear tendency of the residual can be observed in function of the observed

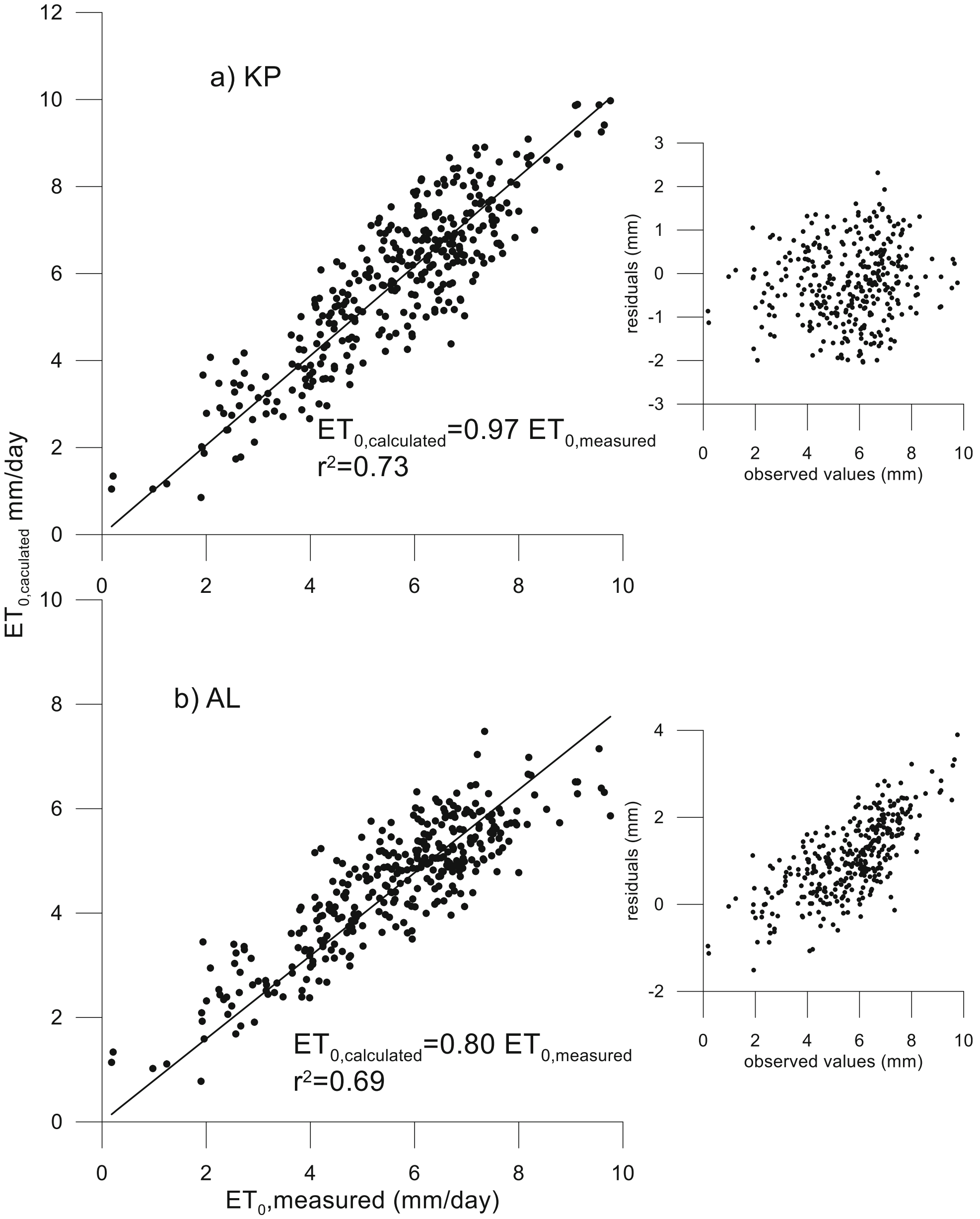


Fig. 7 Comparison at daily scale during four successive summers (2001, 2002, 2003 and 2004) in Rutigliano site between daily reference evapotranspiration ET_0 values calculated by KP (**a**) and AL (**b**) formulas and those directly measured by weighing lysimeter. In the *small panels* on the right, the residuals are plotted against the observed valued by the model

values). Moreover, the index of agreement is equal to 0.93 for KP model and 0.79 for AL model, showing a much better performance of the first model with respect to the second one.

4.2 ET_0 calculated by AL and KP formulas for the future climate change period and impact on IR determination

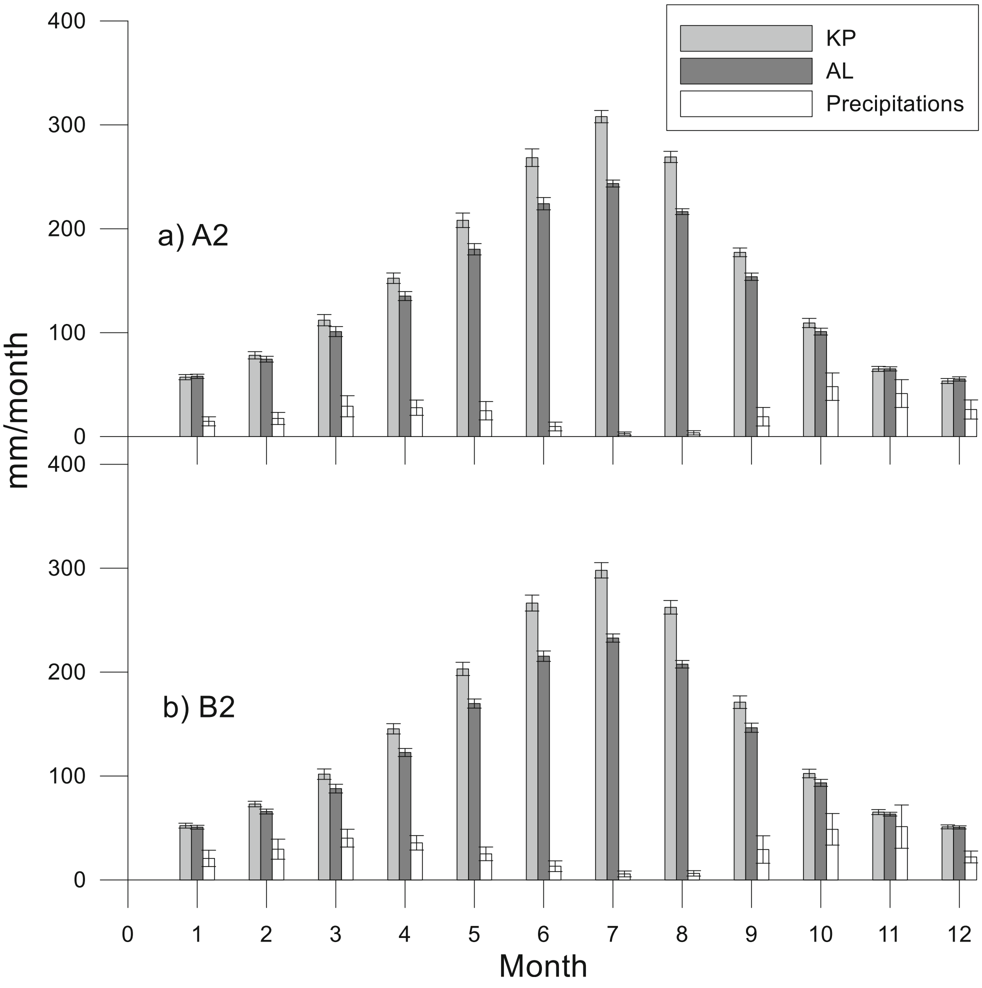
Figure 8 shows the mean values of precipitation and ET_0 on a monthly scale calculated by the AL and KP formulas for the Foggia site during 2070–2100 period for two scenarios of future climate change, A2 (Fig. 8a) and B2 (Fig. 8b). It can be seen that for both scenarios, the ET_0 values are very similar during 5 months (October–February) for both formulas. During the other 7 months, (April–September) the values of ET_0 calculated by the KP formula are strongly and significantly higher than the values calculated by the AL formula.

Furthermore, it can be seen that for both scenarios, the monthly values of ET_0 are now significantly higher than the precipitation, regardless of the used formula, throughout the whole year. Thus, the grass irrigation season will involve most of the year under future climate change scenarios.

This increase has a double origin: the already observed increase in ET_0 for both the AL and KP formulas and the decrease in the forecasted precipitation for the considered scenarios.

On an annual scale (Table 2), the mean annual crop water requirements for the reference crop were calculated as a sum of monthly ET_0 values, which were obtained by the KP formula for the Foggia site for the scenarios A2 and B2, are always higher than those calculated by the AL approach: +13 and +16 % for the

Fig. 8 Mean monthly values in Foggia site of precipitation, reference evapotranspiration ET_0 calculated by Al and KP formulas and standard errors for two scenarios of future climate change A2 (**a**) and B2 (**b**) during 2070–2100 period



scenarios A2 and B2, respectively. These differences are similar to the observed value (+16 %) for the same site within the measured climate change period (see Table 1). Moreover, the two formulas forecast a similar increase in ET_0: +26 % for scenario B2 and +28 and +31 % for scenario A2 for Foggia site. Starting from these forecasted ET_0 values and the forecasted precipitation values, we can see that the difference between the two formulas in the IR annual values varied between 16 % (scenario A2) and 20 % (scenario B2) for Foggia site (see Table 2). The smaller values of annual IR are always relative to the AL formula used for calculating ET_0.

Table 2 Mean annual cumulated values for the site of Foggia, under two scenarios A2 and B2 of future climate during 2070–2100 of reference evapotranspiration ET_0, precipitation P and irrigation requirement (IR) together with standard errors

2070–2100		ET_0	Err.st (ET_0)	*P*	Err.st (*P*)	IR	Err.st (IR)
Rutigliano	KP	1859	18	265	21	1594	33
	AL	1609	14			1344	31
Foggia	KP	1792	14	328	27	1464	35
	AL	1506	10			1178	34

After the comparison of AL and KP ET_0 formulas in two periods (actual measured period of climate change 1981–2006 and future climate 2070–2100), the following observation can be summarized:

- The monthly values of ET_0 calculated by the two formulas during the measured climate change period and the forecasted future climate change periods are very similar during the humid seasons (autumn and winter). During the spring and summer seasons the ET_0 values calculated by the KP formula are higher than those calculated by the AL formula.
- The annual cumulative values of ET_0 calculated in this study by the AL formula are systematically lower than those determined by the KP formula, for both the measured and the forecasted future climate changes periods. The observed differences (13–16 %) are quite stable under both climate change periods.
- The differences between the ET_0 estimations with the AL and KP formulas have a strong impact on the

> determination of the irrigation requirement IR of the reference crop. In fact, for the measured and forecasted future climate periods, the annual values of IR obtained when ET_0 is calculated using the AL formula are systematically lower than those obtained when ET_0 is calculated by the KP formula. During the measured climate change period, the reduction in IR values varied by site from 26 (site of Foggia) to 28 % (site of Rutigliano). During the future climate change period, the reduction at the Foggia site varied from 16 % (scenario A2) to 20 % (scenario B2).

The cause of the observed difference between the values of ET_0 calculated by the two formulas can be interpreted differently according to the considered observation period: the measured climate change period and the forecasted future climate change period. During the measured climate change period, which is characterized by a variation in the air CO_2 concentration in the range 335–380 ppm, the role of the factor *F*, which is dependent on this concentration, can be considered negligible because its value in this range of CO_2 concentrations varied between 0.99 and 1.01 (see. Eq. 12). Therefore, the observed differences in the ET_0 calculation for the two formulas can be attributed only to the parameterisation of r_c, in the KP formula, as it is considered to be constant and equal to 70 s m^{-1} in the AL formula.

To establish which of the two previous formulas better forecast the daily ET_0 measured by weighing lysimeters within the measured climate change period (1981–2006), a comparison was performed during the warm seasons of four successive years (2000, 2001, 2002 and 2004) in Rutigliano between the ET_0 calculated with the AL and KP formulas and the values directly measured by weighing lysimeters. The results demonstrated that the AL formula underestimated the measured ET_0 values by 20 %, whereas the underestimation is only 3 % for the KP formula (see Fig. 7).

During the future climate change period, which is characterized by a variation of air CO_2 concentrations in the ranges 600–850 ppm and 500–600 ppm for scenarios A2 and B2, respectively, the factor *F* becomes significant, as it varied between 0.87 and 0.93 when the CO_2 concentration reached 850 and 600 ppm, respectively. Thus, the observed differences between the annual values of ET_0 calculated by the two formulas represent the balance between two contradictory impacts: the r_c parameterisation, which tended to increase the ET_0 values obtained by the KP formula with respect to ET_0 values obtained by the AL formula during 1981–2006 period, and the factor *F*, which tended to decrease the ET_0 values obtained by the KP formula with respect to values obtained by the AL formula. The stable observed difference (13–16 %) between the annual values of ET_0, calculated by the two formulas under future climate change thus highlights the equilibrium between the two previously identified impacts.

The previous analysis highlighted the inadequacy of the solutions proposed by some authors to adapt the AL formula to future climate change for any proposed solutions: (i) the substitution of the constant daily values of the grass r_c (70 s m^{-1}) with always constant values greater than and close to 85 s m^{-1} (Lovelli et al. 2010) or 87 s m^{-1} (Moratiel et al. 2011) and (ii) the simple correction of the ET_0 values calculated by this formula with the factor *F* (Olioso et al. 2010). In fact, these two solutions always consider the resistance r_c to be constant by neglecting its dependence on climatic variables. The tests performed for the measured climate change period clearly revealed that r_c parameterisation is absolutely necessary to reduce the difference between the ET_0 values calculated by the AL formula and those directly measured.

The estimation of ET_0 in the Mediterranean region obtained here by means of the AL formula is very close to that obtained by other authors using the same formula. For example, the annual values of ET_0 during the period 1981–2006 (1059 ± 32 mm) are strictly equal to the values determined for the same site and for the same period by Campi et al. (2012) and Palumbo et al. (2012). When the same HadCM3 simulation model and scenarios (A2 and B2) were used in other studies conducted in the Mediterranean region (Rodriguez-Diaz et al. 2007; Giannakopoulos et al. 2009; Rodriguez-Diaz and Topcu 2010), the obtained forecasted values of the future water requirement for irrigated crops are consistent with the values obtained in the present study. For example, Rodriguez-Diaz and Topcu (2010) forecast an increase in the water requirement for corn by +17 % in 2050 and +26 % for sunflower crop in Spain in 2080. Furthermore, Giannakopoulos et al. (2009) forecast an increase in the needed irrigation for crops in the Mediterranean region by +40 % between 2030 and 2060. These estimations appear to be close to the values obtained in the present study, i.e. an increase in the water requirement for the reference crop from 26 to 31 % during the 2070–2100 period.

5 Conclusions

The present study focused attention on a possible under-estimation of the water and irrigation requirements both for the present and the future climate changes when an unsuitable evapotranspiration formula is used. This study compares two formulas for calculating the daily evapotranspiration ET_0 for a reference crop. The first formula was proposed by Allen et al. (AL), while the second one was proposed by Katerji and Perrier with the addition of the CO_2 effect on evapotranspiration (KP). The first one considers the canopy resistance as constant and independent on the climate. The performances of KP model were better than the performances of AL model. In fact, in any analysed situation AL underestimated the reference ET. For the water requirements, the under-estimation is on the order of approximately 15 % for the mean on the year scale for the measured and forecast future climate change data. For the irrigation requirements, the under-estimation is, on average, on the order of approximately 18 % for the future climate change period and 28 % for the measured climate change period. These orders of magnitude for underestimated values are large enough that they cannot be neglected in studies devoted to simulating actual and future irrigation scheduling, irrigation system design and water resources planning and management.

The previous conclusion clearly indicates that the hypothesis of Allen et al. (2006), in which the error due to neglecting the variation in crop resistance r_c has little impact on the calculation of ET_0 and, subsequently, on the IR evaluation, can be rejected, particularly in the Mediterranean region, for both the measured climate change and future climate change periods. These conclusions validate the criticisms made by Rana et al. (1994), Steduto et al. (1996), Katerji and Rana (2006, 2011, 2014) and Shuttleworth and Wallace (2009), which were already mentioned in the "Introduction" section of this article.

The application of the KP formula in the studies performed for the future climate change scenarios requires only the determination of the annual concentration of CO_2 in addition to the standard weather variables. These data are supplied for all scenarios in the forecast climates. Thus, we recommend the use of the KP formula instead of the AL formula because it can improve the estimations of ET_0 and IR in arid and semi-arid regions.

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