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RESEARCH ARTICLE

Calculation and Simulation of Evapotranspiration of Applied Water

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Abstract

The University of California, Davis and the California Department of Water Resources have developed a weather generator application program "SIMETAW" to simulate weather data from climatic records and to estimate reference evapotranspiration (ET_o) and crop evapotranspiration (ET_c) with the generated simulation data or with observed data. A database of default soil depth and water holding characteristics, effective crop rooting depths, and crop coefficient (K_c) values to convert ET_o to ET_c are input into the program. After calculating daily ET_c, the input and derived data are used to determine effective rainfall and to generate hypothetical irrigation schedules to estimate the seasonal and annual evapotranspiration of applied water (ET_{aw}), where ET_{aw} is the net amount of irrigation water needed to produce a crop. In this paper, we will discuss the simulation model and how it determines ET_{aw} for use in water resources planning.

Key words: weather generator, water balance, crop water requirements, water resource planning, crop coefficient

INTRODUCTION

The California Department of Water Resources and the University of California developed the "Simulation of Evapotranspiration of Applied Water" application program (SIMETAW) to help the State of California plan for future water demand by agriculture and for landscape irrigation. A main feature of the SIMETAW program is that it simulates daily weather data from monthly climate data for a user-specified period of years. SIMETAW is a user-friendly program that (1) calculates reference evapotranspiration (ET_o) from simulated weather data, (2) determines crop coefficient (K_c) values for a wide range of irrigated crops, (3) accounts for factors affecting the K_c values, (4) calculates crop evapotranspiration (ET_c), (5) computes a hypothetical irrigation schedule for each of the simulated years of data, (6) estimates the effective rainfall and the irrigation water requirement (ET of applied water or ET_{aw}), and (7) calculates the mean ET_{aw} over a specified number of years. When ET_{aw} is divided by the application efficiency, the result is a site-specific total irrigation requirement.

Soil water holding characteristics, effective rooting depths, and irrigation frequency are used with rainfall and ET_c data to calculate a daily water balance and determine effective rainfall and ET_{aw}, which is equal to the seasonal cumulative ET_c minus the effective rainfall minus the change in soil water content from the beginning to the end of the season. Irrigation is timed so that the estimated soil water content does not fall below the

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yield threshold depletion (Y_{TD}), which is calculated from input soil depth, rooting depth, and percentage allowable depletion. In the off-season, the depletion of soil water D_{sw} is allowed to drop to a maximum 50% depletion of the available water in the top 0.3 m. This paper discusses how the simulation model uses monthly climate data to generate daily weather data over variable periods of record and the advantages of the new model over traditional long-term ET_c estimates. The paper also discusses how water balance calculations are used to determine ET_{aw}.

MODEL DESCRIPTION

Entering crop and soil information

Crop and soil information are input into a data file using a comma delimited format so the data are readable by MS Excel. The input data include (1) the crop name, (2) planting and physiological maturity (ending) date, (3) irrigation frequency during initial growth, (4) pre-irrigation information, (5) immaturity factors, (6) presence of cover crops, (7) soil water holding characteristics, and (8) maximum soil and rooting depths. Each row of data in the file contains a unique combination of the crop, soil, and irrigation information.

Crop rooting depth, maximum soil depth, and soil water holding characteristics are used to calculate the yield threshold depletion (Y_{TD}), which is used to make a crop- and soil- specific irrigation schedule. The user selects one of three general categories for the volumetric available water holding capacity (θ_A) in mm H_2O per mm depth of soil. The program uses θ_A=0.075, θ_A=0.125, and θ_A=0.175 mm water per mm soil depth for light, medium, and heavy soils, respectively. The q_A value is multiplied by the effective rooting depth (mm) to determine the plant available water (P_A) in mm within the soil reservoir. The effective rooting depth is selected as the maximum rooting depth or the soil depth, whichever is smaller. Since we are mainly interested in P_A and about half of the water in a typical soil is available water, we assume that field capacity (F_C) is double the P_A, where F_C is the soil water content after drainage of gravitational water. Assuming that F_C is double the P_A does not affect water balance calculations or irrigation timing and amount. The permanent wilting point (P_W) is an estimate of the soil water content where crop roots are essentially unable to extract more water, so F_C is the upper and P_W is the lower soil water content for the P_A. Starting at F_C, water is depleted from the soil until a crop begins to experience mild to moderate water stress at a water content called the yield threshold (Y_T). Then, as the water content continues to decrease towards the P_W, the attraction of water to the soil particles increases, root water extraction becomes increasingly difficult, and the plants are subjected to increasing water stress that reduces crop growth, transpiration, and yield or quality. Note that depletion of soil water (D_{sw}) rather than soil water content is used for water balance scheduling in the SIMETAW model. The depletion of soil water (D_{sw}) is D_{sw}=0 at F_C, and the depletion increases to the yield threshold depletion (Y_{TD}), which corresponds to the water content at the Y_T. The D_{sw} can exceed the Y_{TD} and can increase until it reaches the permanent wilting depletion (P_{WD}), which corresponds to the water content at P_W. As the depletion of soil water increases from the Y_{TD} to the P_W, crops experience water stress that reduces growth, photosynthesis, and transpiration.

The fraction of P_A that falls between F_C and the Y_T is called the allowable depletion (A_D), and it is normally expressed as a percentage. The A_D depends on soil water holding characteristics, plant drought tolerance, and evaporative demand; however, it mainly depends on the root length density (R_{LD}), which is described below. As a soil dries, it dries fastest near the roots where water is taken up by the plants. As the soil near the roots dries, the soil water tension increases, and it becomes more difficult for water to transfer from the wetter soil to the roots. If the distance between wet soil and roots is shorter, then water transfer from the soil to the roots is facilitated and the plants are better able to tolerate dry soil. Thus, crops with more root length per unit volume are better able to transfer water and tolerate water deficits. The R_{LD} is defined as the length of roots per unit volume of soil. Therefore, crops with higher R_{LD} generally have higher A_D values. For example, a lettuce crop has a low R_{LD} and A_D, whereas alfalfa has a fairly high R_{LD} and A_D. Thus, one can deplete more soil water between irrigation events when irrigating alfalfa than when irrigating lettuce. The SIMETAW model allows for input of the A_D with a default value A_D=50%, which is reasonable for most field and horticultural crops. Then, the Y_T is used as a first guess at the depletion of soil water between irrigation events for the water balance calculations.

Other input irrigation factors include selecting whether or not the crop is pre-irrigated (i.e., an irrigation is applied before the crop is planted) and the number of hectares planted. One can enter the percentage ground cover (shading) for immature tree and vine crops. Since some tree and vine crops have cover crops or weeds growing between the rows, SIMETAW adjusts for the contribution of ET from the cover crops as well as from the crop. It is possible to enter the beginning and ending dates for two periods during a season when cover crops are present. This is included to adjust for crops that have cover crops in the winter, spring, and fall but no cover crop in the summer.

Weather simulation

Weather simulation models are often used in conjunction with other models to evaluate possible crop responses to environmental conditions. In SIMETAW, daily crop evapotranspiration (ET_c) is estimated as the product of daily ET_o and a crop coefficient (K_c) value that is appropriate for that day. Daily precipitation data and water balance determined irrigation data are then used with the derived ET_c to determine effective rainfall and ET_{aw}.

Either daily or monthly climate data are used to determine ET_{aw}. If monthly data are used, SIMETAW simulates the daily weather data using a weather generator. For testing purposes, one can also calculate the monthly means from raw daily data and then can generate simulated daily weather data from the calculated means. This feature was included to provide the ability to validate the weather data simulation. SIMETAW can also read comma-delimited monthly climate data from a file to generate daily weather data for a specified period of years.

Daily and monthly data files include solar radiation, maximum and minimum temperature, dew point temperature, and wind speed data. Daily data files include precipitation and the monthly files have the monthly total precipitation and the number of days per month having significant precipitation, where significant precipitation is defined as two times the daily ET_o rate. When daily data are generated from monthly climate data, the program forces a negative correlation between rainfall amount and ET_o rate within each month assuming that rainfall is inversely related to ET_o.

Precipitation

Characteristics and patterns of rainfall are highly seasonal and localized, and a general seasonal model that is applicable to all locations is impossible to generate. Recognizing the fact that rainfall patterns are usually skewed toward extreme heavy amounts and that the rain status of the previous day tends to affect the present day's condition, a Gamma and Markov chain modeling approach is often applied to describe rainfall patterns for periods within which rainfall patterns are relatively uniform (Gabriel and Neumann 1962; Stern 1980; Larsen and Pense 1982; Richardson and Wright 1984). The two-state approach consists of a first order Markov chain and a gamma distribution function. Normally, this type of two-state model requires long-term daily rainfall data to estimate model parameters; however, SIMETAW uses only monthly averages of total rainfall amount and number of rain days to obtain all parameters for the Gamma and Markov Chain models. The method using long-term daily rainfall is called the "LONG" method, and the simplified monthly average method is called the "GENG" method in this paper.

The simplest Markov chain model to simulate rainfall occurrence includes parameters of two transitional probabilities from: (1) a wet day to a wet day ($P(W/W)$) and (2) a dry day to a wet day ($P(W/D)$). The gamma function parameters are α and β, where $\alpha\times\beta$ is the mean, and $\alpha\times\beta^2$ is the variance of the distribution. Occurrence of a wet day is determined by comparing the computer generated random uniform deviates with the estimated transitional probabilities using the derived gamma function parameters. The amount of rainfall for a wet day is generated from α and β estimates based on a method developed by Berman (1971). The challenge is to use monthly means of the number of wet days and rainfall amount to estimate four model parameters.

Through an analysis of large data sets from many weather stations, Geng *et al*. (1986) established the following empirical relationships between the variables that greatly simplified the number of parameters needed to estimate the four functions:

$$P(W/D)=0.75\times(\text{Fraction of wet days in a month}) \quad (1)$$

$$P(W/W)=0.25+P(W/D) \quad (2)$$

$$\beta=-2.16+1.83\times(\text{Per wet day rain amount}) \quad (3)$$

$$\alpha=(\text{Per wet day rain amount})/\beta \quad (4)$$

This simple "GENG" method and the "LONG" method, which requires long-term daily values as input, were compared with observed parameters and the results from Geng *et al*. (1986) are shown in Table 1. Comparison results showed that the simplified "GENG" method performs as well as the "LONG" method, and both methods perform extremely well relative to observed data.

Wind speed

The simulation of wind speed is a simple procedure, requiring only the gamma distribution function, which was previously described for rainfall simulation. While using a gamma distribution provides good estimates of extreme values of wind speed, there is a tendency to infrequently have some unrealistically high wind speed values generated for use in ET_o calculations. Wind speed depends on atmospheric pressure gradients, and there is no correlation between wind speed and the other weather parameters used to estimate ET_o. Therefore, the random matching of high wind speeds with conditions favorable to high evaporation rates leads to unrealistically high ET_o estimates on some days. To eliminate this problem, an upper limit for simulated wind speed was set at twice the mean wind speed. This restriction was believed to be a reasonable upper limit for a weather generator used to estimate ET_o because extreme wind speed values are generally associated with severe storms and ET_o is generally not important during such conditions. Unfortunately, because there is no correlation with other variables used in the ET_o calculation, there still were some days with high wind speed occurring on the same day as high radiation and temperature and low wind speed. This resulted in unrealistic high ET_o values on those days. While we are still working on this problem, it was decided to use the well-known cubic spline fit method to determine daily from monthly wind speed data until a solution to the simulation problem is found. After testing climate data from many climates, we found use of the cubic spline fit for wind speed to be a good temporary solution to the problem.

Temperature, solar radiation, and humidity data typically follow a Fourier series distribution, but the seasonality variation of these variables is somewhat vague in tropical regions. A model for the variables is ex-

Table 1 A comparison of observed rainfall parameters with the "LONG" and "GENG" simulation methods showing the number of wet days and precipitation amount (mm) and the correlations between observed and simulated

Location	Wet days			Precipitation	
	Method	Number	Correlation	Amount	Correlation
Boise	OBSERVED	91		293	
	LONG	90	0.99	289	0.98
	GENG	94	0.99	299	0.99
Boston	OBSERVED	129		1 157	
	LONG	129	0.90	1 175	0.97
	GENG	129	0.87	1 163	0.95
Columbia	OBSERVED	103		877	
	LONG	105	0.95	884	0.99
	GENG	106	0.94	906	0.97
Los Banos	OBSERVED	170		2 063	
	LONG	178	0.99	2 176	0.99
	GENG	172	0.98	2 100	0.99
Miami	OBSERVED	128		1 526	
	LONG	127	0.99	1 535	0.99
	GENG	129	0.99	1 512	0.99
Phoenix	OBSERVED	34		174	
	LONG	34	0.95	180	0.94
	GENG	37	0.95	193	0.97
Wageningen	OBSERVED	187		690	
	LONG	196	0.96	721	0.99
	GENG	189	0.99	708	0.98

pressed as,

$$X_{ki}=\mu_{ki}(1+\delta_{ki}C_{ki}) \tag{5}$$

Where k=1 (represents maximum temperature), k=2 (represents minimum temperature), and k=3 (represents solar radiation). The estimated daily mean is μ_{ki}, and C_{ki} is the estimated daily coefficient of variation on the ith day for i=1, 2, ..., 365 and for the kth variable.

$$\mu_{ki}=\alpha_k+\beta_k \cos\left(\left[\frac{2(i\text{-}q_k)}{365}\right]\right) \tag{6}$$

Where α_k is the annual mean, β_k is the amplitude of the cosine curve for the kth variable, and q_k is the day of the year when the peak of the corresponding kth variable curve occurs. The noise factor, δ_{ki}, is assumed to follow a weakly stationary generating process. Let,

$$D_i=B_0D_{i\text{-}1}+B_1E_i \tag{7}$$

Where D_i is the vector of δ's (i.e., δ_{1i}, δ_{2i}, δ_{3i}) for the ith day and E_i is the error vector of the ith day, which contains random errors that are independently and normally distributed with the mean equal to 0 and variance equal to 1.

$$B_0=R_1R_0^{-1} \tag{8}$$

$$B_1B_1'=R_0\text{-}R_1R_0^{-1}R_1 \tag{9}$$

Where R_0 is the positive definite cross correlation matrix among the three variables and R_1 is the serial correlation matrix with a lag of "-1" day among the three variables. R_0 cannot equal R_1.

The Fourier model was used in Richardson and Wright (1984), but their model depends on long-term daily values as inputs to calculate the model parameters. SIMETO simplified the parameter estimation procedure, and it needs only monthly means as inputs. From a study of monthly data in 34 locations in the USA, the observed coefficient of variation (CV) values were inversely related to the means. Assuming the same CV for daily data, the monthly CV values were used to determine the daily means. In addition, a series of functional relationships between the parameters of the mean curves and the parameters of the coefficient of variation curves made it possible to calculate C_{ki} coefficients from μ_{ki} curves without additional input data.

For maximum temperature,

$$C_{1i}=(0.536\text{-}0.00573\alpha_1) \\ \text{-}\exp(\text{-}4.63+0.0952\beta_1)\cos\left(\frac{2(i\text{-}q)}{365}\right) \tag{10}$$

and for minimum temperature,

$$C_{2i}=\exp(\text{-}0.0466\alpha_2) \\ \text{-}\exp(\text{-}4.64+0.146\beta_2)\cos\left(\frac{2(i\text{-}q)}{365}\right) \tag{11}$$

Temperature and solar radiation are associated with rainfall, and the correlation is accounted for using:

$$d_i=10\ (1\text{-}2f) \tag{12}$$

Where d_i is the temperature difference (°F where °F=1.8°C+32) between the dry and wet days and f is the fraction of number of wet days in a year, where f=0.5 if f >0.5.

$$\mu_i \text{ (temperature °F for a dry day)}=\mu_i+d_i f \tag{13}$$

$$\mu_i \text{ (temperature °F for a wet day)}=\mu_i\text{-}d_i(1\text{-}f) \tag{14}$$

For solar radiation, the mean CV curve is estimated, as in equation 10 for the maximum temperature, except using α_3 and β_3 as described in equation 6 for solar radiation. The d_i for solar radiation is defined as:

$$d_i=|410\text{-}3.12L\text{-}0.35\mu_s| \tag{15}$$

Where L is the latitude and μ_s is the annual mean daily radiation in langleys (note that 1.0 Ly=1.0 cal cm^{-2}=41 830.76 J m^{-2}=0.04183076 MJ m^{-2}).

Results of simulations for maximum and minimum temperature and for solar radiation using data from Davis, CA were compared with observed data (Geng and Auburn 1987) and the results are shown in Figs. 1-3.

Reference evapotranspiration calculation

Reference evapotranspiration (ET_o), for short canopies, is estimated from daily weather data using a modified version of the Penman-Monteith equation (Allen *et al*. 1998, 2005):

$$ET_o=\frac{0.408\Delta(R_n\text{-}G)+\gamma\dfrac{900}{T+273}u_2\,(e_s\text{-}e_a)}{\Delta+\gamma\,(1+0.34\ u_2)} \tag{16}$$

Where Δ (kPa °C^{-1}) is the slope of the saturation vapor pressure curve at mean air temperature, R_n and G are the net radiation and soil heat flux density in MJ m^{-2} d^{-1}, g (kPa °C^{-1}) is the psychrometric constant, T (°C) is the daily mean temperature, u_2 (m s^{-1}) is the mean wind speed, e_s (kPa) is the saturation vapor pressure calculated from T, and e_a (kPa) is the actual vapor pressure calculated from T_d (°C), which is the mean

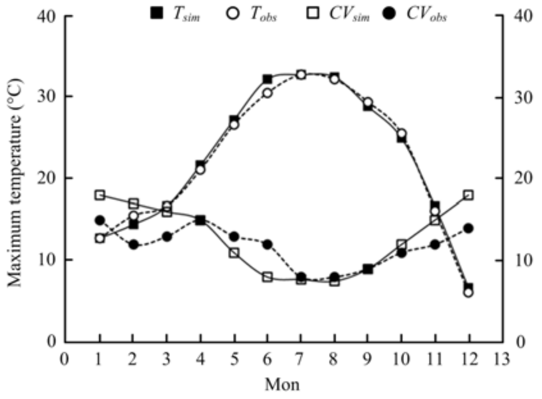

Fig. 1 Simulated (T_{sim}) and observed (T_{obs}) mean daily maximum temperature and simulated (CV_{sim}) and observed (CV_{obs}) coefficient of variation curves for Davis, California.

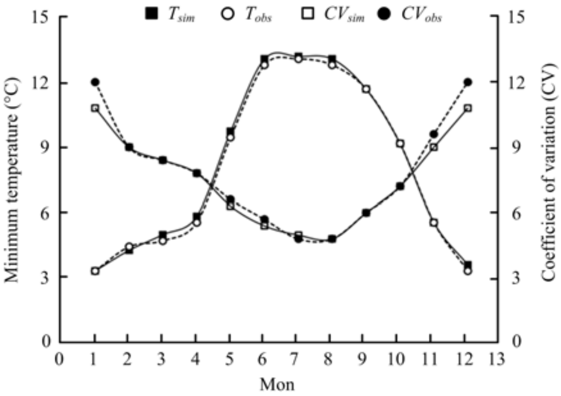

Fig. 2 Simulated (T_{sim}) and observed (T_{obs}) mean daily minimum temperature and simulated (CV_{sim}) and observed (CV_{obs}) coefficient of variation curves for Davis, California.

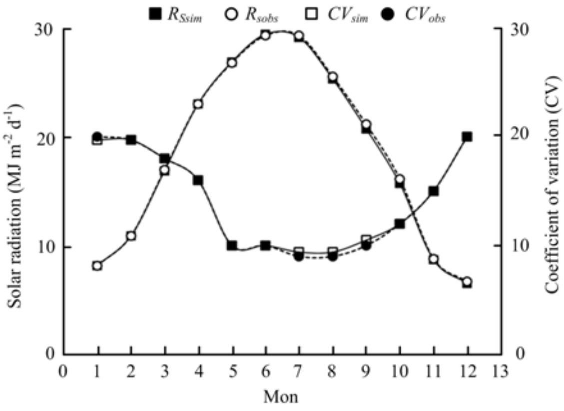

Fig. 3 Simulated (R_{Ssim}) and observed (R_{sobs}) mean daily solar radiation and simulated (CV_{sim}) and observed (CV_{obs}) coefficient of variation curves for Davis, California.

daily dew point temperature. The calculations needed to determine the parameters in equation (16) are well-known and published in Allen *et al.* (1998, 2005). A summary of the main calculation steps is provided in Appendix A.

Bare soil evaporation

During the off-season and during initial crop growth, soil evaporation (E) is the main component of ET_c. Therefore, a K_c for bare soil (K_e) is useful to estimate off-season soil evaporation and the K_c and ET_c during initial growth of crops. A two-stage method for estimating soil evaporation presented by Stroosnijder (1987) and refined by Snyder *et al.* (2000) and Ventura *et al.* (2006) is used to estimate bare-soil crop coefficients. Using a soil hydraulic factor of β=2.6, this method gives K_c values as a function of wetting frequency and ET_o (Fig. 4) that are similar to the widely-used bare soil coefficients that were published in Doorenbos and Pruitt (1977). The soil evaporation model estimates crop coefficients for bare soil using the daily mean ET_o rate and the expected number of days between significant precipitation (P_s) on each day of the year. Daily precipitation is considered significant when P_s>2×ET_o. To avoid confusion, the symbol K_e rather than K_c is used for the bare soil evaporation crop coefficient.

Crop coefficients

While ET_o is a measure of the 'evaporative demand' of the atmosphere, crop coefficients account for the difference between the crop evapotranspiration (ET_c) and ET_o. The main factors affecting the difference are (1) light absorption by the canopy, (2) canopy roughness, which affects turbulence, (3) crop physiology, (4) leaf age, and (5) surface wetness. Because evapotranspiration is the sum of the evaporation (E) from soil and plant surfaces and transpiration (T), which is vaporization that occurs inside of the plant leaves, it is often best to consider the two components separately.

When not limited by water availability, both transpiration and evaporation are limited by the availability of energy to vaporize water. During early growth of crops, ET_c is dominated by soil evaporation and the rate depends on whether or not the soil surface is wet. If a

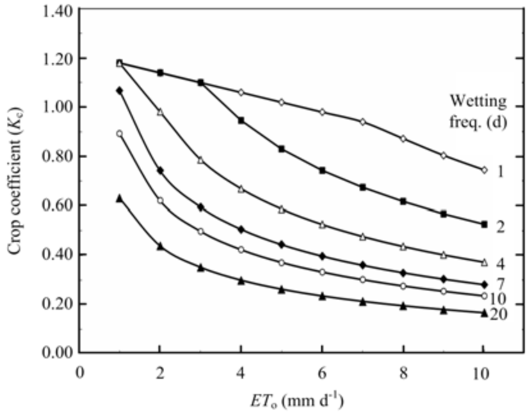

Fig. 4 Evaporation coefficient (K_e) values for nearly bare-soil evaporation as a function of the mean ET_o rate and wetting frequency in days.

nearly bare-soil surface is wet, the ET_c rate varies from slightly higher than ET_o for low evaporative demand to about 80% of ET_o under high evaporation conditions. As a canopy develops, interception of radiation by the foliage increases and transpiration, rather than soil evaporation, dominates ET_c. Field and row crop K_c values generally increase until the canopy ground cover reaches about 75%, and the peak K_c is reached when the canopy of tree and vine crops has reached about 70% ground cover. The ground cover percentage associated with the peak K_c is slightly lower for tree and vine crops because the taller plants intercept more solar radiation at the same percentage ground cover.

Worldwide, the main sources of K_c information are the FAO 24 (Doorenbos and Pruitt 1977) and FAO 56 (Allen *et al*. 1998) papers on evapotranspiration. In those publications, crop growth is described in terms of the growth periods: (1) initial, (2) rapid, (3) midseason, and (4) late season. The publications provide site specific examples of the numbers of days in each growth period. While this method does work for many locations, the growth date information is site specific, and it depends somewhat on cultural practices and climate. Most local farmers do not know the number of days in each growth period and some literature is questionable, so SIMETAW uses the percentage of the season from planting or leaf-out to the end points of the growth stages. Then, a user only needs to input the planting or leaf-out date and the physiological maturity date at the end of the season. All of the dates at the end points of the various growth periods are calculated from the percentages that are stored in tables within the model. This greatly simplifies the K_c curve determination and eliminates the problem to identify the end of the midseason period, which is not easy to visualize. Figs. 5 and 6 show examples of how the percentages of the season match with the end points of growth periods. The seasonal K_c curve determination is discussed below.

Field and row crops

Crop coefficients are determined using a modified Doorenbos and Pruitt (1977) method. The season is separated into initial (date A-B), rapid (date B-C), midseason (date C-D), and late season (date D-E) growth periods (Fig. 5). Tabular default K_c values corresponding to important inflection points in Fig. 5 are stored in the SIMETAW program. Because the K_c value is fixed at one value during initial growth, the K_c value on date A (K_{cA}) is set equal to that on date B (K_{cB}). Although K_{cC} and K_{cD} are equal for most crops, the K_c values for dates C (K_{cC}) and D (K_{cD}) are adjustable for to account for some crops that do change their K_c during midseason. This differs from the method of Doorenbos and Pruitt (1977), who used a fixed value for the K_c between dates C and D. Between dates B and C, the K_c value changes linearly from K_{cB} to K_{cC}. Similarly, the K_c values change linearly from K_{cC} to K_{cD} during midseason and from K_{cD} to K_{cE} during late season. On any given day, if the K_c from the linear interpolation is less than the K_e for bare soil evaporation based on ET_o and rainfall frequency, the higher K_c or K_e value is used. Field and row crops that have changed K_c values during a season are called Type-1 crops. Field and row crops that have nearly the same K_c value for the entire season (e.g., irrigated pasture, turfgrass, and alfalfa averaged over cuttings) are called Type-2 crops. Appendix B lists crop growth information and tabular K_c values for default planting and physiological maturity for some major field and row crops.

Tree and vine crops

Deciduous tree and vine crops are called Type-3 crops, and subtropical crops (e.g., citrus, avocados, olives, etc.) are called Type-4 crops. Deciduous trees and

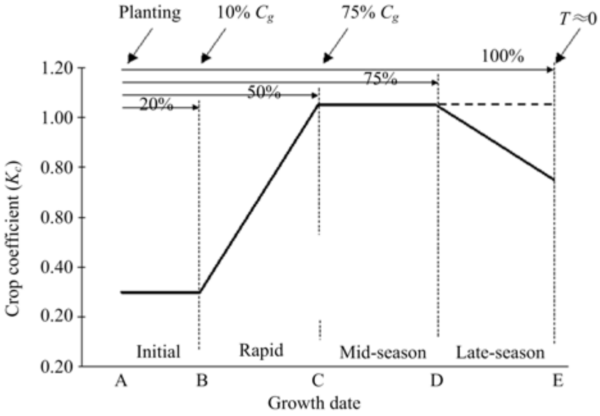

Fig. 5 Hypothetical crop coefficient (K_c) curve for typical field and row crops showing the growth stages and percentages of the season from planting to critical growth dates. Inflection points in the K_c curve occur at 10 and 75% ground cover (C_g) and at the onset of late season (date D). The season ends when transpiration (T) from the crop ceases ($T\approx0$).

vines, without a cover crop, have similar K_c curves to field and row crops but without the initial growth period (Fig. 6). The K_c values depend on (1) energy balance characteristics, (2) canopy structure effects on turbulence, and (3) plant physiology differences between the crop and reference crop. The season begins with rapid growth at leaf-out when the K_c increases from K_{cB} to K_{cC}. The midseason period begins at approximately 70% ground cover and generally the K_c value is fixed at K_{cC} until the onset of senescence on date D. Therefore, K_{cD} is usually equal to K_{cC}, but SIMETAW allows K_{cD} to be changed if the crop coefficient is known to change during midseason. In late season, when the crop leaves are senescing, the K_c decreases from K_{cD} to K_{cE}. The end of the season occurs at physiological maturity or after the first frost when the tree or vine transpiration is near zero. At any time during the season, if K_c values are less than the K_e for bare soil evaporation based on ET_o and rainfall frequency on the same date, the higher K_c or K_e value is used. It is possible to make adjustments for the presence of a cover crop. With a cover crop, the K_c values for deciduous trees and vines are increased by 0.35 depending on the amount of cover. However, the K_c is not permitted to exceed 1.20. Type 4 orchard crops are assumed to have a fixed K_c value for the entire season, but the values are corrected for growth, cover crops, and rainfall. Appendix B lists crop growth information and tabular K_c values for default leaf out and physiological maturity dates for major orchard and vine crops

Correcting the K_c for immature orchards and vineyards

SIMETAW accounts for immaturity effects on crop coefficients for tree and vine crops. Immature deciduous tree and vine crops use less water than mature crops. The following equation is used to adjust the mature K_c values (K_{cm}) as a function of percentage ground cover (C_g).

$$\text{If } \sin\left(\frac{C_g\pi}{140}\right)\geqslant 1.0 \text{ then } K_c=K_{cm}$$

$$\text{else } K_c=K_{cm}\sin\left(\frac{C_g\pi}{140}\right) \tag{17}$$

For an immature orchard, the mature K_c values (K_{cm}) are adjusted for their percentage ground cover (C_g) using the following criteria.

$$\text{If } \sqrt{\sin\left(\frac{C_g\pi}{140}\right)}\geqslant 1.0 \text{ then } K_c=K_{cm}$$

$$\text{else } K_c=K_{cm}\sqrt{\sin\left(\frac{C_g\pi}{140}\right)} \tag{18}$$

Correcting for cover crops

With a cover crop, the K_c values for deciduous trees and vines are higher. When a cover crop is present, 0.35 is added to the clean-cultivated K_c. The peak K_c,

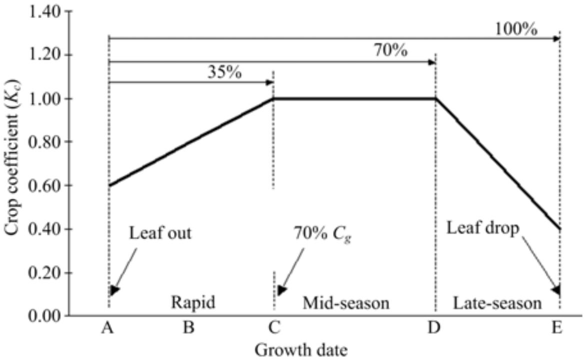

Fig. 6 Hypothetical crop coefficient (K_c) curve for typical deciduous orchard and vine crops showing the growth stages and percentages of the season from leaf out to critical growth dates. Inflection points occur at 70% ground cover (C_g) and at the onset of late season (date D).

however, is not allowed to exceed K_c=1.20. Since a ground cover will continue to transpire during the leafless period of deciduous trees and vines, the K_c values are not allowed to fall below K_c=0.90. SIMETAW allows beginning and ending dates to be entered for two periods when a cover crop is present in an orchard or vineyard.

Crop evapotranspiration

In SIMETAW, reference evapotranspiration is calculated from either input raw or simulated daily weather data. Based on input crop, soil, and irrigation information, the seasonal K_c curves are determined, and daily crop evapotranspiration (ET_c) is calculated as the product $ET_c=ET_o\times K_c$ on each day. A sample plot of the ET_o, K_c, and ET_c for a maize crop is shown in Fig. 7. The annual ET_o data was simulated using SIMETAW and the Davis, California climate data. The K_c curve was determined using SIMETAW and the default information for maize (Appendix B).

Water balance calculations

During the off-season, ET_c is estimated from the product of ET_o and the evaporation coefficient (K_e) as: $ET_c=ET_o\times K_e$. For effective rainfall calculations, it is assumed that all water additions to the soil come from rainfall and losses are only due to deep percolation. Because the water balance is calculated each day, rainfall runoff onto a cropped field is ignored. Likewise, water running onto a cropped field is also ignored. If rainfall run-on is a local problem, then one can correct for the "run-on" by adding rainfall to maintain the soil water content at field capacity until the soil begins to dry.

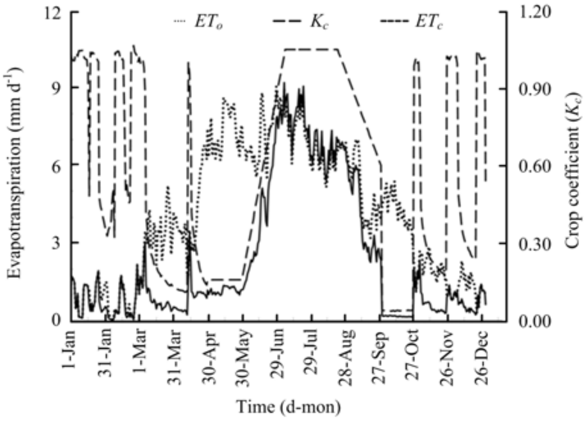

Fig. 7 Crop (ET_c) and reference (ET_o) evapotranspiration and crop coefficient (K_c) factors for maize using one year of simulated weather data to calculate ET_o.

While the Y_{TD} provides an estimate of how much water to deplete between irrigation events, making a water balance schedule based on the Y_{TD} will not consistently provide a reasonable output because the D_{sw} should be sufficiently low that the soil is dry enough to allow a farmer to harvest. Therefore, rather than using the Y_{TD}, a management allowable depletion (M_{AD}) that is less than or equal to the Y_{TD} is used. The M_{AD} is found using the following procedure.

During the off-season, the M_{AD} is determined as 50% of the P_A in the upper 30 cm of soil. It is assumed that soil evaporation is minimal once 50% of the available water in the upper 30 cm of soil is removed. If the D_{sw} is less than M_{AD}, the ET_c is added to the previous day's D_{sw} to estimate the current D_{sw}. Once the D_{sw} reaches the M_{AD}, it remains at the maximum depletion unless rainfall decreases the depletion to less than M_{AD}. If rainfall occurs, the D_{sw} is decreased by the rainfall amount but never less than zero, which corresponds to field capacity (F_C). If the D_{sw} at the end of a cropping season starts at some value greater than the maximum depletion of soil water, the D_{sw} is allowed to decrease with rainfall additions, but it is not allowed to increase with ET_c (Fig. 8).

If a crop is pre-irrigated, then the D_{sw} is set equal to zero on the day preceding the season. If it is not pre-irrigated, then the D_{sw} on the day preceding the season is determined by water balance during the off-season before planting or leaf-out. The D_{sw} is set equal to zero on December 31 preceding the first year of data. After that, the D_{sw} is calculated using a continuous daily water balance for the entire period of record. Therefore, the water balance from the previous year will affect the initial D_{sw} at the beginning of a new year.

During the growing season, the D_{sw} is updated by adding the ET_c on the current day to the D_{sw} on the previous day. If rainfall occurs, D_{sw} is reduced by an amount equal to the rainfall. However, the D_{sw} is not allowed to be less than zero. This automatically determines the effective rainfall as equal to the recorded rain-

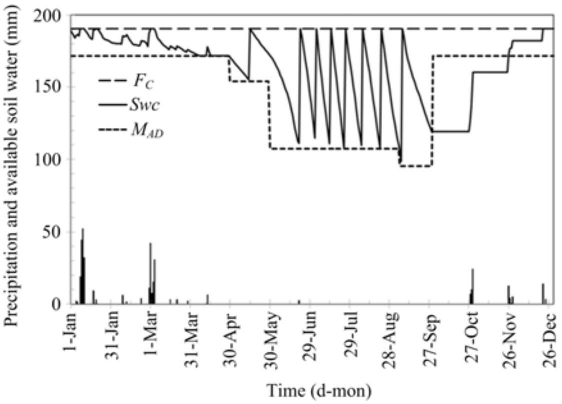

Fig. 8 An annual water balance for a maize crop showing fluctuations in soil water content (S_{wc}) between field capacity (F_C) and the management allowable depletion (M_{AD}) and precipitation (P). The daily weather data were generated using one year of climate data from Davis, California.

fall if the amount is less than the D_{sw}. If the recorded rainfall is more than the D_{sw}, then the effective rainfall equals the D_{sw}. This method ignores runoff and water running on to the field, but this is a minor problem in most irrigated fields. Irrigation events are timed on dates when the D_{sw} would exceed the Y_{TD}. It is assumed that the D_{sw} returns to zero (i.e., F_C) on each irrigation date. A sample plot of a seasonal water balance for a maize crop that was not pre-irrigated is shown in Fig. 8.

Some crops are frequently irrigated with sprinklers during the initial crop growth period (i.e., from date A to date B). In SIMETAW, if frequent sprinkler irrigation is practiced, it is possible to set the number of days between irrigation events during the initial growth period. For example, if a lettuce crop is sprinkler irrigated every 3rd d during initial growth, the first irrigation is applied at 3 d after planting and every 3 d thereafter until reaching the rapid growth period. After the initial growth period, irrigation events occur on the date when the D_{sw} would exceed the M_{AD}. In all cases, for an irrigation occurring on the *i*th date, the $N_{A,i}=D_{sw,i-1}+ET_{c,i}-P_i$, where $N_{A,i}$ is the net application amount, $D_{sw,i-1}$ is the depletion of soil water the day before irrigation, and $ET_{c,i}$ and P_i are the crop evapotranspiration and precipitation amounts on the irrigation date. The $N_{A,i}$ is never allowed to be less than zero, which might occur on a heavy rainfall day.

The $M_{AD}=Y_{TD}$ during the initial and late season growth periods. The M_{AD} during rapid and midseason growth stages is determined by first calculating the number of irrigation events during those stages as:

$N_{\mathrm{I}}=\mathrm{int}\left(\frac{CET_{crm}}{Y_{TD}}+1\right)$ and then computing $MAD=\frac{CET_{crm}}{N_I}$

Where Y_{TD} is the yield threshold depletion, N_{I} is the number of irrigation events, and CET_{crm} is the cumulated crop evapotranspiration during the rapid and midseason periods. This scheduling approach is used so that the D_{sw} is close to the Y_{TD} at the end of the season in most years.

Evapotranspiration of applied water

Evapotranspiration of Applied Water (ET_{aw}) is the sum of the net irrigation applications to a crop during its growing season, where each net irrigation application (N_A) is equal to the product of the gross application (G_A) and an application efficiency fraction (A_E), i.e., $N_A=G_A\times A_E$. The G_A is equivalent to the applied water, and the application efficiency is the fraction of G_A that contributes to crop evapotranspiration (ET_c). Two methods to determine ET_{aw} are explained below using the maize crop as an example. The ET_o, ET_c, and K_c values for two sample years were shown in Fig. 4 and the water balance was shown in Fig. 5.

For all crops, daily water balance calculations start with the soil water content on the previous day (θ_{i-1}). Then, the water losses to evapotranspiration on the current day ($ET_{c,i}$) are subtracted to determine the soil water content on the current day as: $\theta_i=\theta_{i-1}-ET_{c,i}$. The soil water content is adjusted for effective rainfall by comparing the precipitation (P_i) with the soil water depletion on the *i*th day ($D_{sw,i}=ET_{c,i}+D_{sw,i-1}$). If $P_i<ET_{c,i}+D_{sw,i-1}$, then the effective rainfall on the *i*th day is $E_{r,i}=P_i$. Otherwise, $E_{r,i}=ET_{c,i}+D_{sw,i-1}$. The final estimate of soil water content on the *i*th day, without considering irrigation, is expressed as:

$\theta_i=\theta_{i-1}-ET_{c,i}+E_{r,i}$

Irrigation is applied whenever the $D_{sw,i}$ reaches the management allowable depletion ($M_{AD,i}$) on the *i*th day. The net application ($N_{A,i}$) amount is the depth of water needed to raise the soil water content (θ_i) back to field capacity (F_C). On each irrigation date, the $N_{A,i}$ is equal to $D_{sw,i}=F_C-\theta_i$, so the soil water content on each day of the season is calculated as:

$$\theta_i=\theta_{i-1}-ET_{c,\,i}+E_{r,\,i}+N_{A,\,i} \qquad (20)$$

Where $N_{A,\,i}=0$ on non-irrigation days and $D_{sw,\,i}$ is the soil water depletion below F_C:

$$D_{sw}=F_c-\theta_i \qquad (21)$$

By definition, ET_{aw} is the amount of applied irrigation water that contributes to ET_c; therefore, ET_{aw} is the sum of the N_A values during a cropping season:

$$ET_{aw}=N_{A,\,1}+N_{A,\,2}+N_{A,\,3}+N_{A,\,4}+\ldots+N_{A,\,n} \qquad (22)$$

Alternatively, ET_{aw} equals the seasonal total evapotranspiration (CET_c) minus the seasonal total effective rainfall contribution (CE_r) minus the change in soil water content (θ_A-θ_E) from the beginning (θ_A) to the end (θ_E) of the season (Fig. 9). Thus, ET_{aw} is determined by (1) calculating the seasonal CET_c and subtracting seasonal CE_r and $\Delta S_{wc}=(\theta_A-\theta_E)$ as shown in Fig. 9 or (2) summing the net irrigation applications during the season (Fig. 8). If all of the crop and soil information are input into the model, SIMETAW provides an estimate of the net irrigation requirements for the ET_o region under study. If irrigation methods are matched with the crops and an estimate of application efficiency is available for the various systems, the gross application requirement can be determined as:

$$G_A=\frac{N_A}{E_A} \qquad (23)$$

Where E_A is the application efficiency (fraction) of the irrigation system. This provides planners with information on water diversion requirements for a region having similar ET_o.

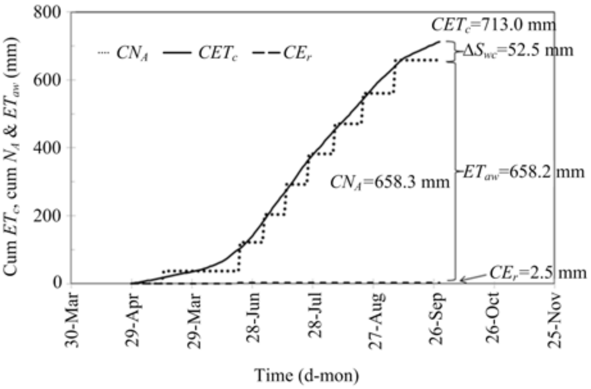

Fig. 9 A plot of cumulative net application (CN_A), cumulative crop evapotranspiration (CET_c), and effective rainfall (CE_r) for a maize crop using one year of simulated weather from the Davis, California monthly climate data and the default crop coefficient information (Appendix B). The evapotranspiration of applied water is: $ET_{aw}=CN_A$ or $ET_{aw}=CET_c-\Delta S_{WC}-CE_r$.

Evaluation of the simulation model

To test the accuracy of SIMETAW, 9 yr of daily measured weather data (1990-1998) from the Davis station (#6) of the CIMIS network (Snyder and Pruitt 1992) were used to simulate 9 yr of daily weather data. The mean daily climate data were calculated from the daily data by month, and the monthly means were used to generate the simulated data. The weather data consist of solar radiation (R_s), maximum (T_x) and minimum (T_n) temperature, wind speed at 2 m height (u_2), dew point temperature (T_d), and rainfall (P). In all cases, the comparison between observed and simulated data was good (Figs. 10-15). Data from several other CIMIS stations in a range of climates showed similar good simulation of observed data.

SIMETAW simulation and climate change

The weather generator in SIMETAW allows us to investigate how climate change could affect the water demand within a study area. For example, by increasing or decreasing the monthly solar radiation, temperature, and/or dew point temperature, the impact on ET_o, ET_c, and ET_{aw} is easily assessed. In addition, the CO_2 concentration affects canopy resistance and the impact of higher CO_2 concentration on evapotrans-

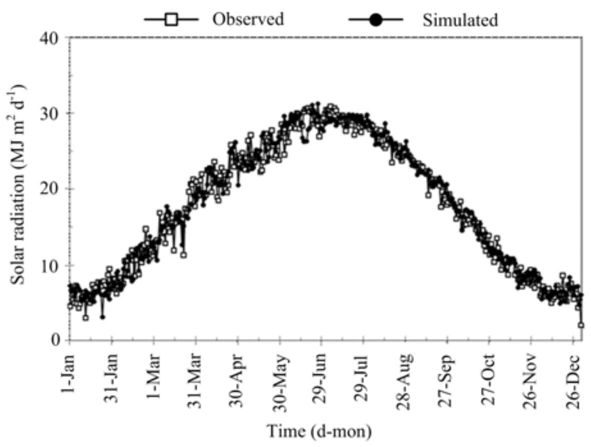

Fig. 10 Comparison of 9 yr means of measured and simulated solar radiation data from Davis, California.

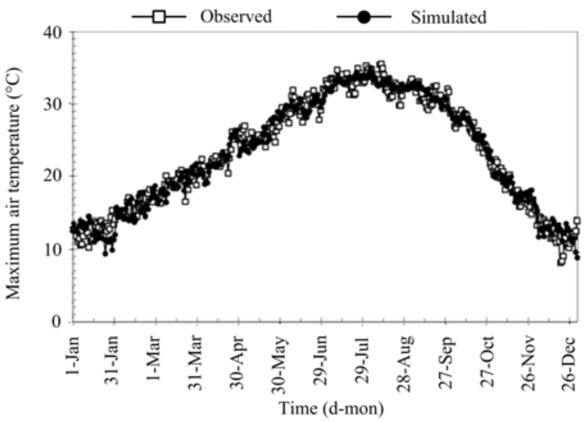

Fig. 11 Comparison of 9 yr means of measured and simulated maximum air temperature data from Davis, California.

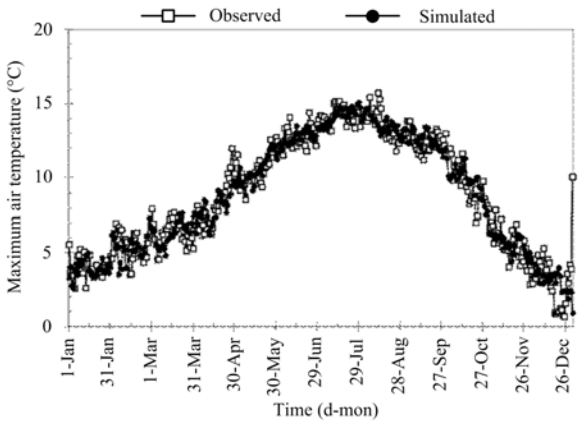

Fig. 12 Comparison of 9 yr means of measured and simulated minimum air temperature data from Davis, California

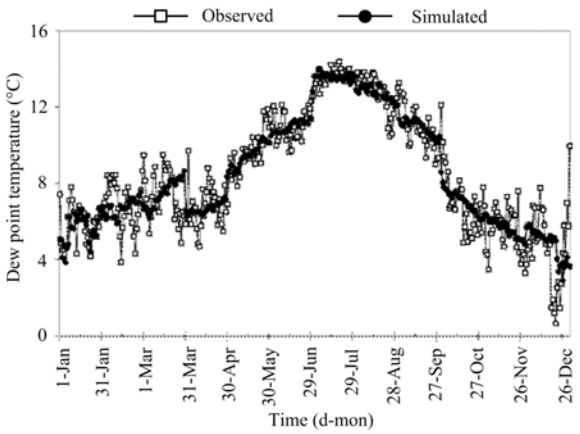

Fig. 13 Comparison of 9 yr means of estimated and simulated dew point temperature data from Davis, California.

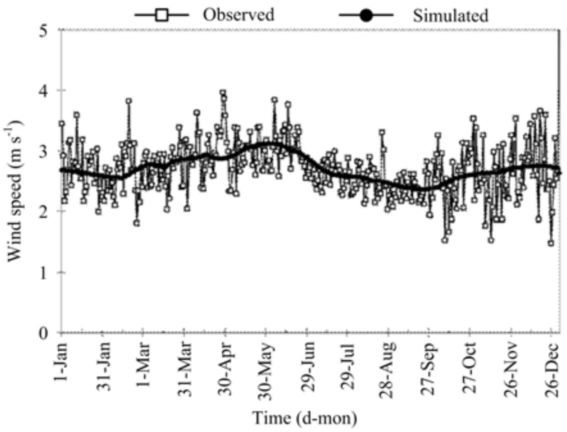

Fig. 14 Comparison of 9 yr means of estimated and generated wind speed data from Davis, California. Note that the wind speed was generated with a cubic spline fit of the monthly means.

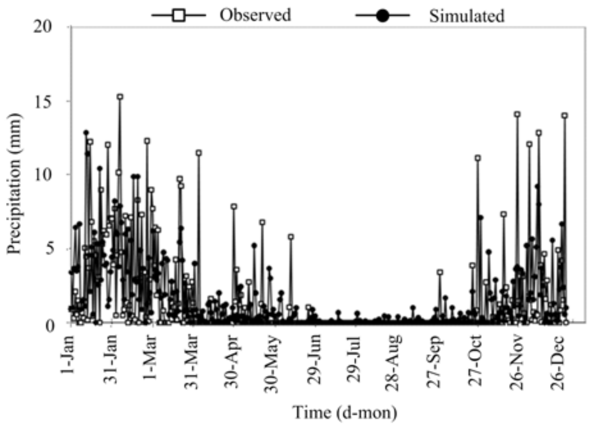

Fig. 15 Comparison of 9 yr means of estimated and simulated rainfall data from Davis, California.

piration is often ignored. SIMETAW, however, estimates the effect of increased canopy resistance on evapotranspiration. Since SIMETAW also generates daily from monthly rainfall data, it also offers the ability to determine the impact of changing rainfall patterns on the water balance and ET_{aw}.

Using monthly mean data from Davis, California, the SIMETAW model was run using four different scenarios:

1) No changes to the current monthly mean data;

2) All monthly maximum and minimum temperatures were increased by 3°C;

3) The same as scenario 2, but also increasing the monthly mean dew point temperatures by 3°C;

4) The same as scenario 3, but also increasing the

canopy resistance from 70 to 87 s m^{-1}.

Relative to scenario 1, the mean daily ET_o rates for an average year increased 18% (scenario 2), 8.5% (scenario 3), and 3.2% (scenario 4). A plot of the mean over 30 years of the simulated scenario data is shown in Fig. 16. This example shows that increases in dew point and canopy resistance can at least partially offset increases in ET_o resulting from higher air temperature.

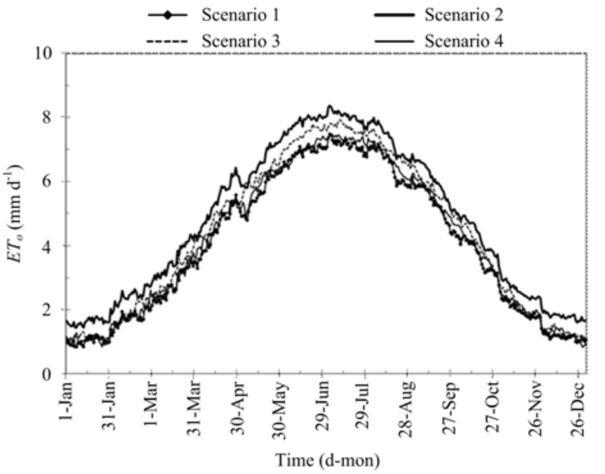

Fig. 16 A plot of the mean simulated daily ET_o for Davis, California using scenario 1 (current conditions), scenario 2 (air temperatures increased by 3°C), scenario 3 (air and dew point temperature increased by 3°C), and scenario 4 (all temperatures increased by 3°C and the canopy resistance increased from 70 to 87 s m^{-1}).

CONCLUSION

The SIMETAW application model to simulate weather data, estimate reference and crop evapotranspiration, compute crop water balance, and estimate evapotranspiration of applied water was presented. During a growing season, a daily water balance using estimated crop evapotranspiration, input soil water holding characteristics, input crop rooting depth, and an irrigation schedule, based on yield threshold depletions, is used to estimate effective rainfall by subtracting percolation losses to deep percolation. During the off-season, soil water balance is computed using estimated soil evaporation and simulated rainfall. Seasonal evapotranspiration of applied water is calculated as the accumulated total of daily crop evapotranspiration minus effective rainfall and the change in root zone water content. The annual evapotranspiration of applied water is computed in the same manner.

Appendix associated with this paper can be available on http://www.ChinaAgriSci.com/V2/appendix

References

Allen R G, Pereira L S, Raes D, Smith M. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. *FAO Irrigation and Drainage Paper*. 56, FAO, Rome.

Allen R G, Walter I A, Elliott R L, Howell T A, Itenfisu D, Jensen M E, Snyder R L. 2005. *The ASCE Standardized Reference Evapotranspiration Equation*. American Society of Civil Engineers. Reston, Virginia. p. 192.

Berman M B. 1971. *Generating Gamma Distributed Variates for Computer Simulation*. **12**, 1241-1247.

Doorenbos J, Pruitt W O. 1977. Guidelines for predicting crop water requirements. *FAO Irrigation and Drainage Paper*. 24, FAO, Rome.

Duffie J A, Beckman W A. 1980. *Solar Engineering of Thermal Processes*. John Wiley and Sons, New York. pp. 1-109.

Gabriel K R, Neumann J. 1962. A markov chain model for daily rainfall occurrence at Tel Aviv. *Quarterly Journal of the Royal Meteorological Society*, **88**, 90-95.

Geng S, Penning de Vries F W T, Supit I. 1986. A simple method for generating daily rainfall data. *Agricultural and Forest Meteorology*, **36**, 363-376.

Geng S, Auburn J. 1987. Weather simulation models based on summaries of long-term data. In: *International Symposium on Impact of Weather Parameters on the Growth and Yield of Rice*. April 7-10, 1986. IRRI. Manila, Philippines.

Larsen G A, Pense R B. 1982. Stochastic simulation of daily climate data for agronomic models. *Agronomy Journal*, **74**, 510-514.

Snyder R L, Bali K, Ventura F, Gomez-MacPherson H. 2000. Estimating evaporation from bare or nearly bare soil. *Journal of Irrigation and Drainage Engineering*, **126**, 399-403.

Snyder R L, Pruitt W O. 1992. Evapotranspiration data management in California. In: *Irrigation and Drainage Session Proceedings Water Forum 1992*. Baltimore, MD, USA. pp. 128-133.

Richardson C W, Wright D A. 1984. *WGEN: a Model for Generations Daily Weather Variables*. USDA-ARS-8, Springfield, VA.

Stern R D. 1980. The calculation of probability distribution for models of daily precipitation. *Archiv* für *Meteorologie, Geophysik und Bioklimatologie* (Serie B). vol. 28. Spring-Verlag, New York. pp. 137-147.

Stroosnijder L. 1987. Soil evaporation: test of a practical approach under semi-arid conditions. *Netherlands Journal of Agricultural Science*, **35**, 417-426.

Ventura F, Snyder R L, Bali K M. 2006. Estimating evaporation from bare soil using soil moisture data. *Journal of Irrigation and Drainage Engineering*, **132**, 153-158.

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