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Evaluation of two evapotranspiration approaches simulated with the CSM–CERES–Maize model under different irrigation strategies and the impact on maize growth, development and soil moisture content for semi-arid conditions

J. Anothai[a,*], C.M.T. Soler[a], A. Green[b], T.J. Trout[c], G. Hoogenboom[a]

[a] AgWeatherNet, Washington State University, Prosser, WA 99350-8694, USA
[b] AgroFresh, Inc., Philadelphia, PA 19196-2399, USA
[c] Water Management Research Unit, Natural Resources Research Center, USDA-ARS, Fort Collins, CO 80526-8119, USA

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ABSTRACT

Water deficit is the most common adverse environmental condition that can seriously reduce crop productivity. Crop simulation models could assist in determining alternate crop management scenarios to deal with water-limited conditions. However, prior to the application of crop models, the appropriate performance under different soil moisture levels should be confirmed. The objective of this study was to evaluate the capability of the CSM–CERES–Maize model to simulate the impact of different irrigation regimes on maize (*Zea mays* L.) growth and development, evapotranspiration and soil water content under semi-arid conditions. Data from irrigation trials that were conducted in 2008 and 2010 in northeast of Greeley, Colorado were used for this assessment. The irrigation treatments were 100, 85, 70, 55 and 40% of full crop water requirements. The daily evapotranspiration (ET) was measured using Bowen ratio-energy balance (BREB) instrumentation. The ability of the CSM–CERES–Maize model using two different ET approaches, i.e., Priestley–Taylor (PT) and FAO-56 Penman–Monteith (PM), in reproducing the experimental maize growth and development data as well as the daily and seasonal ET measured with the BREB method, and soil water content based on different water regimes was analyzed. The results showed that the model with both the PT and FAO-56 PM approach simulated phenology accurately for all irrigation treatments. The CSM–CERES–Maize model simulated both grain yield and final biomass fairly well for all irrigation levels for both ET approaches. The normalized root mean square error was less than 10.2% for grain yield and 36.8% for final biomass for the PT approach and 12.1% for grain yield and 26.0% for final biomass for the FAO-56 PM approach. The model using the PT approach provided daily and seasonal ET values that had a slightly lower accurate than those derived from the FAO-56 PM approach as compared the measured ET by the BREB method. However, the model with both two ET approached could simulate daily and seasonal ET within 12% of measured ET. There was a reasonable agreement between the simulated and observed water content for all four soil depths of the six irrigation treatments which were derived from both approaches. In addition, the model accurately simulated the fluctuation and time span of the cyclic variation of soil water. Overall, it can be concluded that the CSM–CERES–Maize model using the two different ET approaches, i.e., PT and FAO-56 PM, was able to accurately simulate crop development and yield as well as ET and soil water content in response to the different irrigation regimes under semi-arid conditions. These results also confirmed that the model has the potential for use as a tool for agricultural water management under water-limited conditions.

1. Introduction

Scarcity of water is the most common adverse environmental condition that can affect crop growth and development and can cause a substantial loss of crop yield (Eck, 1986; Lamm et al., 1994). An integrated approach that accounts for water as well as crop, soil and field management could be used to cope with drought stress resulting from soil, weather or limited irrigation. For instance, one can determine a suitable planting date to take advantage of available soil water and precipitation, employing effective irrigation management strategies and increasing the available soil water for crop growth through other appropriate agronomic management

* Corresponding author. Tel.: +1 509 786 9281; fax: +1 509 786 9370.
E-mail addresses: j.anothai@wsu.edu, jakarat@uga.edu (J. Anothai).

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practices (Debaeke and Aboudrare, 2004). Normally, field experiments over multiple locations and years are needed to determine optimum crop management practices that are suitable for water-limited conditions for individual crops or locations. This process is labor-intensive, time consuming and expensive. In addition, the selected test environments may not represent the full range of soil and precipitation variability.

Crop simulation models contain mathematical equations that describe the basic flow and conversion processes of the carbon, water and nitrogen balances that are integrated hourly or daily by a computer program to predict the time course of crop growth, nutrient uptake and water use, and to predict final yield and other plant traits (Boote et al., 2010). Crop simulation models are now so advanced that they can be used as a multipurpose tool for various applications, ranging from decision support for crop management at a farm level to advancing understanding of agricultural research (Boote et al., 1996; Tsuji et al., 1998; Hoogenboom, 2000; Jones et al., 2003). Several of the most common crop models have been evaluated extensively and have been used for a range of applications (Tsuji et al., 1998). Examples include the evaluation of alternate irrigation scheduling strategies (Heinemann et al., 2002; Panda et al., 2004; Dogan et al., 2006; Guerra et al., 2007; Soler et al., 2012), the determination of optimum planting dates (Ruiz-Nogueira et al., 2001; Nabb et al., 2004; Soler et al., 2007; Banterng et al., 2010), the variation in cultivar response to environment (Anothai et al., 2009b; Putto et al., 2009) and adaptation and mitigation strategies under climate change (Boote et al., 2008a).

The Cropping System Model (CSM)–CERES–Maize is the core crop model of the Decision Support System for Agrotechnology Transfer (DSSAT) (Hoogenboom et al., 1999, 2011; Jones et al., 2003) for the simulation of maize growth, development and yield. This model can be used to determine how variations in environmental conditions, management decisions and genetics interact, and how they affect maize growth and development (Garrison et al., 1999). The drought stress index is one of several outputs of the CSM–CERES–Maize model that could be used as guidance for determining optimum irrigation management decisions that conserve water and maximize yield. This index indicates the frequency and severity of drought stress during the cropping season and ranges from a value of zero to one. Under well-watered conditions, the index is zero. Once drought stress occurs, it increases to a value above zero that is proportional to the severity of the stress, with one representing maximum stress.

As part of the simulation of the soil and plant water dynamics, the CSM–CERES–Maize model has two approaches for computing potential evapotranspiration (ET). The first is the Priestley–Taylor evapotranspiration (PT) method (Priestley and Taylor, 1972) and the second is the daily FAO-56 Penman–Monteith (PM) model (Allen et al., 1998). The PT approach is used as the default in the DSSAT software because it uses less weather data than the FAO-56 PM approach, which requires wind speed and relative air humidity as additional inputs (Boote et al., 2008b). Traditionally, the FAO-56 PM model requires a crop coefficient (K_c) concept to calculate ET of different crops, but the DSSAT crop models use crop leaf area index over the season to predict dynamic K_c for transpiration. The potential ET is partitioned to potential plant transpiration and potential soil evaporation based on the Ritchie approach (Ritchie, 1972), which considers the portion of solar energy that reaches the soil surface and that can be spent as latent energy to evaporate water from the soil surface if the soil is wet. Additional information regarding the CSM–CERES–Maize ET theory can be found in Sau et al. (2004) and DeJonge et al. (2012). As part of the daily soil-water balance simulation, the CSM–CERES–Maize model uses the Ritchie (1998) one-dimensional "tipping bucket" approach which is homogenous horizontally and consists of a number of vertical soil layers, to simulate soil water flow and root water uptake for each individual soil layer.

It is well-known that ET is a very important parameter in irrigation management because the remaining soil water content in the individual soil layers is determined primarily by the ET value (Sau et al., 2004). Accurate ET estimates could help with the improvement of irrigation efficiency, reduce irrigation application costs, optimize yield and ultimately increase net returns. Therefore, the capability of simulating ET in CSM–CERES–Maize model is important and requires evaluation with observed ET data. Satisfactory results in studies that evaluated the growth and yield response of the CSM–CERES–Maize model under various irrigation strategies have been reported by Ben Nouna et al., 2000; Panda et al., 2004; Dogan et al., 2006; Saseendran et al., 2008). However, there are no published studies that have compared simulated ET by the CSM–CERES–Maize model with observed ET derived from the Bowen ratio-energy balance instrumentation (Bowen, 1926) under semi-arid conditions. Because the CSM–CERES–Maize model provides two alternate ET approaches, prior to the applications of the model, users might be interested on how simulated plant growth and water responses are affected by the PT versus FAO-56 PM approach. Also, a new version of the CSM–CERES–Maize model (Version 4.5) has been developed (Hoogenboom et al., 2011). Further investigations are needed to evaluate the performance of the model for a range of irrigation treatments. The objective of this study was to evaluate the simulation of maize development and yield, evapotranspiration and soil water content by the CSM–CERES–Maize model using two different ET calculation approaches and a range of water regimes under semi-arid conditions.

2. Materials and methods

2.1. Field experiments

The field data that were used in this study were obtained from the USDA-ARS Water Management Research Unit experimental site located northeast of Greeley, Colorado (latitude 40°26′ N, longitude 104°38′ W, and elevation 1428 m above mean sea level) (Trout and Bausch, 2012). The climate at the site is a semi-arid steppe with a mean annual precipitation of 250 mm and a mean annual maximum and minimum daily air temperature of 17 and 1 °C, respectively. The experiments were conducted during the period from May to November in 2008 and from May to October in 2010. A hybrid maize variety, i.e., DeKalb 52-59 AF2 (VT3) with a 102-day relative maturity, was planted on May 12, 2008 and May 11, 2010 at a plant population of 80,000 plants ha^{-1}. The experiment consisted of six treatments with four replications per treatment. The six irrigation treatments were randomized within each replication. Each experimental plot consisted of 12 rows, 43 m long, with a spacing of 0.76 m between rows. The soil at the location was a fine sandy loam classified as Olney soil series (mesic Ustollic Haplargid). The profile and property information of the soil were obtained from the website of the United Stated Department of Agriculture Natural Resources Conservation Service (National Cooperative Soil Survey, 2012). Fertilizer as urea–ammonium–nitrate (UAN) was applied at planting and then with irrigation water during the growing seasons as needed based on estimated plant growth and expected N uptake. Total N applied was 134 kg N ha^{-1} in 2008 and 146 kg N ha^{-1} in 2010 for all treatments.

2.2. Irrigation treatments

A surface drip irrigation system with 1.6 cm diameter tubing, 30 cm emitter spacing and 1.1 l h^{-1} emitter discharge rate was used to insure uniform water applications within plots (Point Source Irrigation 41T163-12).[1] The thick-wall drip tubing was placed beside each plant row following emergence. The flow rates and volumes for each treatment were measured with turbine flow meters (BadgerMeter Recordall 1½″ Turbo 160 m with RTR transmitters). The irrigation applications for each treatment were controlled and recorded with a Campbell Scientific CR1000 data logger. For the 2008 season, a portable sprinkler system (Nelson Poly 2000 with R10 Turbo heads on 9 m spacing) was used on May 21 to incorporate herbicides and insure uniform germination.

The irrigation treatments consisted of different irrigation amounts based on crop requirements (using soil water content measurements) and supported by potential evapotranspiration estimated based on the atmospheric variables measured by the on-site weather station. The irrigation water treatments considered in the study were 100% (T_1), 85% (T_2), 70% (T_3), 70% (T_4), 55% (T_5) and 40% (T_6) of full crop water requirements. In T_3, the treatment was applied proportional to T_1 at each irrigation application of T_1, whereas treatments T_2, T_4, T_5 and T_6 were targeted to be seasonally proportional to T_1 which was approximately 10% of the projected irrigation amount was withheld during mid-to-late vegetative stages and added back during reproductive stages (with some flexibility from week to week). Irrigations were applied once or twice weekly between mid-June and early September, unless superseded by precipitation. Irrigation was applied to a treatment only if the requirement exceeded 12 mm. The seasonal total number of irrigation applications and total amount of water applied ranged from 10 irrigations with 157 mm in 2008 and nine irrigations with 113 mm in 2010 for the driest treatment (T_6) to 16 irrigations (459 mm) in 2008 and 13 irrigations (366 mm) in 2010 for the full crop water requirements treatment (T_1) (Table 1). All treatments were irrigated equally during the germination and plant establishment period in order to insure emergence and a good plant stand in 2008, but no initial irrigation needed in 2010 due to a wet May.

2.3. Soil moisture and evapotranspiration measurements

Soil water content was determined in each plot between a soil depth of 0–200 cm. The measurements were made starting at 30 days after planting and at several intermediate times during the growing seasons for a total 24 and 23 observation times in 2008 and 2010, respectively. Soil water content at the 0–15 cm depth was measured with a MiniTrase Portable Time Domain Reflectometry (TDR) device. Soil water content for the deeper layers at 30, 60, 90, 120, 150 and 200 cm, was measured with a neutron attenuation probe (503 DR Hydroprobe moisture meter, Campbell Pacific Nuclear, Martinez, CA) from a steel access tube ($1^{1/2\prime\prime}$ electrical conduit) installed in the center of each plot.

Crop evapotranspiration (ETc) measurements were made with the Bowen ratio-energy balance (BREB) instrumentation installed in the center of a 2.4 ha field adjacent to the irrigation plot. The BREB field was planted and managed the same as the main plots and the maize was irrigated to meet full water requirements (100%). The BREB ETc measurements were made every 30 min and summed to daily values starting at 30 and 38 days after planting in 2008 and 2010, respectively.

[1] Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Dept. of Agriculture.

2.4. Crop characteristics

Plant measurements were taken periodically to measure the response of maize to the irrigation treatments. The plant growth stages or phenology for each treatment were assessed visually. For the vegetative phase, phenological development was recorded by counting the number of true leaves. The silking stage was recorded when silks were visible outside the husks on 50% of the plants of each plot. Physiological maturity was recorded when there were visible black layers at the kernel's attachment of the sampled cob. The data on grain yield and total dry matter were destructively sampled at maturity. Final grain harvest was conducted by harvesting approximately 70 m^2 from the center of each maize plot and normalizing weight to 15.5% moisture content.

2.5. Simulation studies

To determine the performance of the CSM–CERES–Maize model in reproducing the observed variables based on different water regimes, the response of the model with two different ET approaches, PT and FAO-56 PM, phenological development and growth as well as evapotranspiration and soil water content was analyzed. The inputs for the model include cultivar information, soil profile characteristics, local daily weather conditions and management practices (Hunt et al., 2001; Jones et al., 2003). The cultivar coefficients for the hybrid maize DeKalb 52-59 AF2 were estimated with the data from the full crop water requirements treatment (T_1) of the 2008 season. This included the silking and physiological maturity dates as well as final grain yield and final total biomass. Although, the experiments were conducted during two growing seasons (2008 and 2010), only the data collected in 2008 were used for model calibration. We wanted to keep the data collected during the 2010 season as a truly independent data set for model evaluation purposes. The Genotype Coefficient Calculator (GENCALC) program (Hunt, 1993) of the Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.5 was used for the optimization of the cultivar coefficients. The CSM–CERES–Maize model requires six cultivar coefficients that define the growth and development characteristics or traits of a maize cultivar (Table 2). The systematic approach and order for calibration followed the procedures described by Boote (1999) and Anothai et al. (2009a), as summarized here: the first step was to select the cultivar coefficients for a typical medium-maturity variety from the DSSAT database as a starting point. Then, the coefficients for P1 and P2 (all variable names used are listed in Table 2) were adjusted until the simulated date of silking date matched the observed. The next step was adjusted the values of P5 to fit the observed physiological maturity. The reproductive growth parameters G2 and G3 were calibrated next, using measured end-of-season grain yield and total biomass.

The soil profile data of the Olney soil series from National Cooperative Soil Survey (2012) plus from field observed were used for soil inputs. The soil information derived from the National Cooperative Soil Survey was the physical and chemical characteristics including soil texture (percentage sand, silt and clay), bulk density, soil organic matter, pH in water, soil nitrogen (N) and cation exchange capacity for each soil horizon. The water holding characteristics of the soil profile for the individual irrigation treatment and experimental year were obtained from field estimated field capacity (water content approximately 24–48 h after a large water application) and soil water at wilting point was assumed to be 50% of field capacity based on Rawls et al. (1982) and Ma et al. (2009) (Table 3). Note that in this study the model was calibrated to the dataset by adjusting only the plant parameters and the soil parameters were kept at their default values without changes during model calibration as mentioned previously. The weather data were obtained from an automated weather station

Table 1
Details of the individual irrigation applications and rainfall events for the 2008 and 2010 growing seasons.

2008								2010							
DAP[b]	Irrigation (mm)						Rainfall (mm)	DAP	Irrigation (mm)						Rainfall (mm)
	T_1[a]	T_2	T_3	T_4	T_5	T_6			T_1	T_2	T_3	T_4	T_5	T_6	
10	21.0	21.0	21.0	21.0	21.0	21.0		1							28.4
24							20.0	6							6.3
25							10.0	10							15.2
39	10.1	10.1	10.1	10.1	10.1	10.1		32	6.4	6.4	6.4				40.1
44	30.2	22.4	21.4	22.6	15.8	16.3		35							36.3
51	39.0	37.3	30.7	31.0	24.6	18.2		44	30.4	24.3	21.5	11.9	12.1	12.0	
58	30.1	21.2	20.7	30.4				47							4.1
65	39.8	27.7	24.9	15.3	27.1	15.8		50	30.1	24.2	21.1	15.1			
68	24.1	17.7	17.1					55							19.8
72	32.4	22.7	22.1	21.3	22.3	18.9		59	30.7	23.9	20.6	18.6	12.6	12.6	
75	28.5	21.3	19.0	15.5				65							7.4
79	26.4	20.5	17.6	18.4	15.7	15.7		67	31.9	26.9	23.4	19.1	17.7	5.4	
82	28.6	25.8	18.4	21.3	19.9	16.0		72	30.1	25.1	21.1	23.1	18.1	12.2	
86	22.4	21.3	15.3	22.5	17.8	14.1		79	42.2	37.2	30.2	32.3	27.2	22.7	
87							42.0	81							18.6
94	23.3	23.0	13.7	14.3	11.6			85	40.2	34.3	24.4	28.2	20.3	12.1	
96							64.5	91	0.44	0.32	0.51	0.51	0.51	0.51	32.8
97							30.8	98	38.6	30.7	23.6	28.7	14.5	10.5	
108	39.5	14.3	9.7	10.3				102	25.1	20.1	18.1	12.1			
115	32.5	26.8	21.0	21.8	15.3	11.4		105							8.6
122	31.2	25.9	20.5	16.6				107	30.2	12.1	15.1	15.1	21.1	25.1	
124							33.8	114	30.1	25.2	21.1	15.1	15.1		
154							8.63	155							8.1
Total	459.1	359.0	303.2	292.4	201.2	157.5	209.7	Total	366.4	290.7	247.1	219.8	159.2	113.1	225.8

[a] T_1 (100%), T_2 (85%), T_3 (70%), T_4 (70%), T_5 (55%) and T_6 (40%) of full crop water requirements.
[b] DAP: days after planting.

(Colorado Agricultural Meteorological Network station GLY04, http://ccc.atmos.colostate.edu/~coagmet/) which was located at the edge of the maize trial area. The data included daily maximum and minimum air temperatures (°C), daily total solar radiation (MJ m^{-2} day^{-1}) and daily total precipitation (mm), as well as wind speed (km day^{-1}) at 2 m height and relative air humidity, which are the additional weather inputs required for the FAO-56 PM approach. General information on agronomic management consisted of planting date, plant population (seed ha^{-1}), row spacing (cm), planting depth (cm), and the dates, amounts and type of fertilizer applications. The schedules and amounts of each individual irrigation application as shown in Table 1 were used as input for allowing the model to mimic different irrigation strategies.

2.6. Statistics

The statistical indicators of percentage difference, the index of agreement (d) (Willmott et al., 1985) and the normalized root mean square error (RMSEn) (Loague and Green, 1991) were computed to determine the degree of predictability. With respect to the percentage difference, a positive value indicates an overestimation, while a negative value indicates an underestimation.

The value of d-index was computed using the following equation:

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (|P_i'| + |O_i'|)^2} \right], \quad 0 \le d \le 1 \tag{1}$$

where n = number of observations, P_i = predicted value for the ith measurement, O_i = observed value for the ith measurement, $\overline{O}$ = the overall mean of observed values, $P_i' = P_i - \overline{O}$ and $O_i' = O_i - \overline{O}$.

The RMSEn was computed using the following equation:

$$\text{RMSEn} = \frac{\text{RMSE} \times 100}{\overline{O}} \tag{2}$$

where RMSE = root mean square error which was computed using the following equation:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (P_i - O_i)^2}{n}} \tag{3}$$

A high value for the d-index and a low value for RMSEn indicate a good fit between the simulated and observed values.

Table 2
Final values of the calibrated cultivar coefficients for the CSM–CERES–Maize model.

Abbreviation	Definition	Unit	Value
P1	Thermal time from seedling emergence to the end of the juvenile phase during which the plant is not responsive to changes in photoperiod	degree-days	267.6
P2	Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate, which is considered to be 12.5 h	days	0.81
P5	Thermal time from silking to physiological maturity	degree-days	586.0
G2	Maximum possible number of kernels per plant	kernels plant^{-1}	960.5
G3	Kernel filling rate during the linear grain filling stage and under optimum conditions	mg day^{-1}	9.42
PHINT	The interval in thermal time between successive leaf tip appearances (phylochron interval)	degree-days	48.0

Table 3
Field capacity (FC) and permanent wilting point (WP) estimated from field measured soil water content and bulk density obtained from National Cooperative Soil Survey for different soil layers and irrigation treatments for the 2008 and 2010 growing seasons.

Soil depth (cm)	Bulk density ($g\ cm^{-3}$)	T_1[a]		T_2		T_3		T_4		T_5		T_6	
		FC ($cm^3\ cm^{-3}$)	WP ($cm^3\ cm^{-3}$)	FC ($cm^3\ cm^{-3}$)	WP ($cm^3\ cm^{-3}$)	FC ($cm^3\ cm^{-3}$)	WP ($cm^3\ cm^{-3}$)	FC ($cm^3\ cm^{-3}$)	WP ($cm^3\ cm^{-3}$)	FC ($cm^3\ cm^{-3}$)	WP ($cm^3\ cm^{-3}$)	FC ($cm^3\ cm^{-3}$)	WP ($cm^3\ cm^{-3}$)
2008 growing season													
0–15	1.52	0.271	0.135	0.264	0.132	0.261	0.131	0.249	0.125	0.249	0.125	0.256	0.128
15–45	1.61	0.260	0.130	0.267	0.134	0.254	0.127	0.246	0.123	0.246	0.123	0.259	0.130
45–75	1.64	0.236	0.118	0.234	0.117	0.226	0.113	0.193	0.097	0.203	0.101	0.227	0.114
75–105	1.65	0.215	0.107	0.186	0.093	0.197	0.098	0.166	0.083	0.170	0.085	0.191	0.095
105–135	1.59	0.198	0.099	0.185	0.093	0.173	0.086	0.146	0.073	0.151	0.076	0.174	0.087
135–175	1.56	0.182	0.091	0.174	0.087	0.165	0.082	0.130	0.065	0.122	0.061	0.135	0.068
2010 growing season													
0–15	1.52	0.238	0.119	0.248	0.124	0.240	0.120	0.233	0.116	0.215	0.108	0.243	0.121
15–45	1.61	0.215	0.108	0.228	0.114	0.231	0.115	0.214	0.107	0.207	0.103	0.226	0.113
45–75	1.64	0.215	0.108	0.208	0.104	0.219	0.109	0.178	0.089	0.190	0.095	0.214	0.107
75–105	1.65	0.193	0.096	0.243	0.121	0.195	0.098	0.208	0.104	0.188	0.094	0.233	0.116
105–135	1.59	0.220	0.110	0.220	0.110	0.234	0.117	0.215	0.108	0.247	0.124	0.233	0.117
135–175	1.56	0.255	0.128	0.241	0.121	0.238	0.119	0.269	0.134	0.253	0.126	0.251	0.126

[a] T_1 (100%), T_2 (85%), T_3 (70%), T_4 (70%), T_5 (55%) and T_6 (40%) of full crop water requirements.

3. Results and discussion

3.1. Growth and development

3.1.1. Phenology

The full crop water requirements treatment (T_1) of the 2008 season was used for model calibration, including determining the values for the cultivar characteristics. The cultivar coefficients derived from model calibration by using either the PT or FAO-56 PM approach as ET input, were identical (Table 2). This was due to the fact that the T_1 treatment had an adequate water supply to meet the ET demands throughout the growing season and represented close to potential production without stress, which are preferred conditions for determining the cultivar coefficients. The calibrated model correctly simulated days from planting to silking and from planting to physiological maturity using both ET approaches. The simulated and observed values were the same, i.e., 86 and 150 days after planting, respectively (Table 4). This indicated that, following calibration of the model, the cultivar coefficients for the hybrid maize could accurately simulate the silking and physiological maturity stages.

Performance evaluation of the CSM–CERES-Maize model in predicting phenology with the independent data sets of the 2008 season under various water stress regimes (T_2 to T_6) using the PT and FAO-56 PM approach for ET calculation, showed that the PT approach simulated the duration from planting to silking reasonably well, with identical results for all evaluation data sets, i.e., 86 days between planting and silking (Table 4). Likewise, the duration from planting to physiological maturity was also in good agreement with the corresponding observed values for all irrigation treatments, i.e., 150 days between planting and physiological maturity. Similar to the PT approach, the simulated number of days from planting to silking and from planting to physiological maturity for the FAO-56 PM approach were identical with the observed values for the treatments that were used for model evaluation (T_2 to T_6) of the 2008 season, i.e., 86 and 150 days for silking and physiological maturity days, respectively (Table 4).

For the 2010 season, the model using either the PT or FAO-56 PM approach simulated days from planting to silking were slightly greater than the corresponding observed values for the treatments (T_1 to T_6). The observed values showed that maize reached the silking stage around 81 days after planting. The model with both two ET calculation approaches simulated silking day difference from the observed values for 4 days, i.e., 85 days between planting and silking (Table 4). On the other hand, the model using both two ET approaches underestimated the duration from planting to physiological maturity for all irrigation treatments in 2010. The simulated physiological maturity date was 136 days after planting compared to the observed 141 days after planting (Table 4).

Delayed silk emergence of one to eight days in response to water deficits during or just prior to anthesis has been reported by other researchers (Robins and Domingo, 1953; Vincent and Woolley, 1972; Herrero and Johnson, 1981; Grant et al., 1989; Nesmith and Ritchie, 1992). However, the datasets in this study did not show any variation in the number of days to silking and physiological maturity among the irrigation treatments. Both the full irrigation and other irrigation treatments reached each developmental stage on the same day.

3.1.2. Grain yield and final biomass

The calibrated model was able to correctly simulate measured grain yield for the full crop water requirements treatment (T_1) of the 2008 season with both ET calculation approaches, whereas for final total biomass, the simulated values were greater than the observed values with the percentage difference less than 22.0% (Tables 5 and 6). Thus, the CSM–CERES-Maize model using the two

Table 4
Simulated and observed for phenological characteristics for the different irrigation treatments using two different ET approaches with the CSM–CERES–Maize model.

Treatment	Phenological charactistic (days)	Observed	Simulated PT	Simulated FAO-56 PM
Model calibration				
T_1 (2008)	Planting to silking	86	86	86
	Planting to physiological maturity	150	150	150
Model evaluation				
T_2–T_6 (2008)	Planting to silking	86	86	86
	Planting to physiological maturity	150	150	150
T_1–T_6 (2010)	Planting to silking	81	85	85
	Planting to physiological maturity	141	136	136

Table 5
A comparison between simulated (Sim.) and observed (Obs.) and percentage difference for grain yield of maize under different irrigation treatments using two different ET approaches with the CSM–CERES–Maize model.

Treatment[a]	2008					2010				
	Grain yield (t ha^{-1})			Difference (%)		Grain yield (t ha^{-1})			Difference (%)	
	Sim. PT	Sim. FAO-56 PM	Obs.	Sim. PT	Sim. FAO-56 PM	Sim. PT	Sim. FAO-56 PM	Obs.	Sim. PT	Sim. FAO-56 PM
Model calibration										
T_1	13.23	13.23	13.23 ± 0.24	0	0					
Model evaluation										
T_1						12.16	11.93	11.17 ± 0.67	8.92	6.81
T_2	13.22	13.16	12.94 ± 0.09	2.25	1.74	11.76	10.64	11.44 ± 0.24	2.75	−7.00
T_3	13.15	11.51	12.60 ± 0.09	4.34	−8.67	9.83	8.69	10.46 ± 0.54	−6.08	−16.94
T_4	13.08	11.90	11.35 ± 0.43	15.26	4.87	9.15	8.19	9.32 ± 0.33	−1.78	−12.13
T_5	10.59	8.48	9.01 ± 1.20	17.59	−5.86	6.53	6.19	7.15 ± 0.61	−8.70	−13.51
T_6	9.42	8.08	8.82 ± 0.87	6.79	−8.48	4.90	4.59	5.50 ± 0.27	−11.02	−16.62
RMSEn[b] (%)				10.22	6.32				6.72	12.11
d[b] (%)				0.97	0.99				0.98	0.94

[a] T_1 (100%), T_2 (85%), T_3 (70%), T_4 (70%), T_5 (55%) and T_6 (40%) of full crop water requirements.
[b] Calculation from treatments used for model evaluation.

ET approaches was able to simulate grain yield and final biomass for the hybrid DeKalb 52-59 AF2 under full crop water requirements.

For model evaluation, the CSM–CERES–Maize model using the PT approach simulated grain yield for all evaluation data sets satisfactorily, i.e., T_2 to T_6 for the 2008 season and T_1 to T_6 for the 2010 season. However, the simulation tended to overestimate yield in 2008 and tended to underestimate yield in 2010. For the 2008 season, the percentage difference with the PT approach ranged from 2.3 to 17.6%, with an average value of 10.2% for the RMSEn for T_2 to T_6 and an average *d*-index of 0.97. For the 2010 season, the model using the PT approach simulated grain yield closer to the observed grain yield than with the FAO-56 PM approach. The percentage difference varied from −11.0 to 8.9% and the mean value for RMSEn and *d*-index were 6.7% and 0.98, respectively, for T_1 to T_6 in 2010 (Table 5). The simulated final biomass with the PT approach was somewhat larger than the observed values for all treatments for both the 2008 and 2010 seasons. The percentage difference ranged from 16.5 to 40.1% for the 2008 season and from 31.7 to 47.6% for the 2010 season. The RMSEn between observed and simulated final biomass was 30.8% and the *d*-index value was 0.62 for the 2008 season, while RMSEn was 36.8% and the *d*-index value was 0.68 for the 2010 season (Table 6).

Table 6
A comparison between simulated (Sim.) and observed (Obs.) and percentage difference for total biomass of maize under different irrigation treatments using two different ET approaches with the CSM–CERES–Maize model.

Treatment[a]	2008					2010				
	Grain yield (t ha^{-1})			Difference (%)		Grain yield (t ha^{-1})			Difference (%)	
	Sim. PT	Sim. FAO-56 PM	Obs.	Sim. PT	Sim. FAO-56 PM	Sim. PT	Sim. FAO-56 PM	Obs.	Sim. PT	Sim. FAO-56 PM
Model calibration										
T_1	26.90	26.90	22.11 ± 0.03	21.66	21.66					
Model evaluation										
T_1						25.22	24.59	18.88 ± 1.02	33.55	30.23
T_2	26.57	26.72	21.58 ± 0.39	23.12	23.81	24.66	22.54	18.73 ± 0.58	31.70	20.35
T_3	25.97	23.94	20.03 ± 0.82	29.67	19.54	22.13	19.83	16.26 ± 0.46	36.09	21.91
T_4	25.21	23.66	18.00 ± 0.75	40.10	31.44	20.44	18.38	15.16 ± 0.63	34.81	21.21
T_5	19.64	16.60	14.18 ± 0.82	38.47	17.06	17.00	15.25	11.52 ± 0.39	47.59	32.43
T_6	16.70	14.94	14.33 ± 0.74	16.54	4.27	13.14	11.94	9.29 ± 0.60	41.33	28.52
RMSEn[b] (%)				30.84	22.69				36.83	26.03
d[b] (%)				0.62	0.77				0.68	0.80

[a] T_1 (100%), T_2 (85%), T_3 (70%), T_4 (70%), T_5 (55%) and T_6 (40%) of full crop water requirements.
[b] Calculation from treatments used for model evaluation.

For the FAO-56 PM approach, the model in general performed satisfactorily for grain yield for all irrigation treatments for both experimental seasons. In most cases, simulated grain yield for the 2008 season was closer to the observed data than grain yield simulated with the PT approach. The percentage difference ranged from −8.7 to 4.9% for the 2008 season and from −16.9 to 6.8% for the 2010 season. The average values for RMSEn and the *d*-index were 6.3% and 0.99 for the 2008 season and 12.1% and 0.94 for the 2010 season (Table 5). Simulated final biomass for the FAO-56 PM approach also exceeded but was closer to the observed final biomass compared to the final biomass simulated by the PT approach for all irrigations for both the 2008 and 2010 seasons. The percentage difference values ranged from 4.3 to 31.4% for the 2008 season and from 20.4 to 32.4% for the 2010 season. Their average values of RMSEn were 22.7 and 26.0% and the *d*-index were 0.77 and 0.80 for the 2008 and 2010 seasons, respectively (Table 6).

The CSM–CERES-Maize model using the FAO-56 PM approach generally simulated grain yield in 2008 and total biomass in both 2008 and 2010 with closer agreement to the observed data than those simulated using the PT approach. One reason could be that the FAO-56 PM approach uses a more mechanistic approach than the PT approach because of the aerodynamic term. In addition, it also uses more weather variables as input that are normally not recorded by standard weather stations. When using the FAO-56 PM approach, minimum and maximum air temperature, solar radiation, wind speed and relative air humidity are required, while only minimum and maximum air temperature and solar radiation are needed for the PT approach.

3.2. Daily and seasonal evapotranspiration

The model was only calibrated for phenology, yield and yield components as described in the previous sections. Therefore, the measured ET for the T_1 treatment was also included for evaluation of the simulated ET by the CSM–CERES-Maize model. The two different ET approaches in the model, PT and FAO-56 PM, were compared with the measured ET using the BREB technique. ET was only measured for the full irrigation treatment, thus the evaluation of the ET approach in the model was only performed for the full crop water requirements treatment of the 2008 and 2010 seasons.

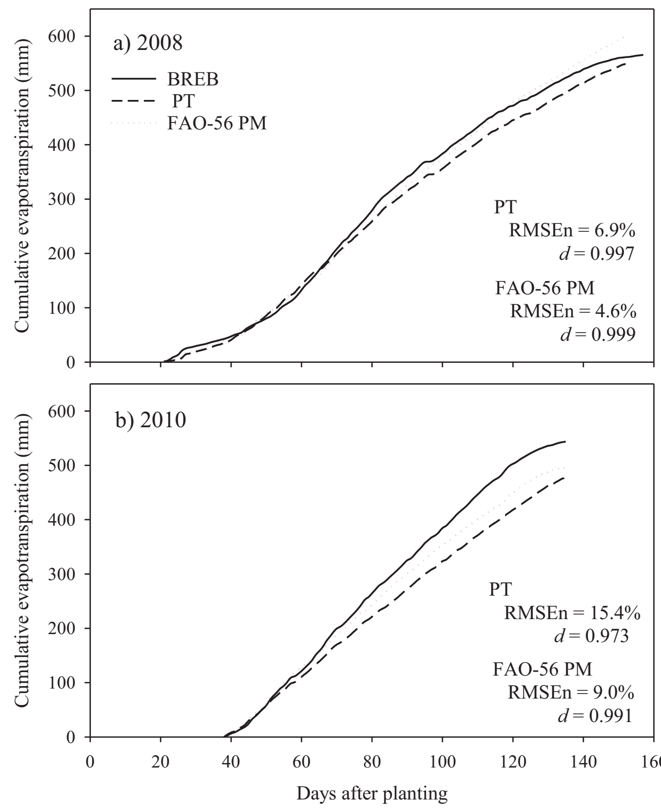

Fig. 1. Cumulative evapotranspiration measured with the Bowen ratio-energy balance (BREB) system, simulated using the Priestley–Taylor (PT) approach and simulated using FAO-56 Penman–Monteith (PM) approach for the full crop water requirements treatment (T_1) of the 2008 season (a) and the 2010 season (b).

The cumulative ET for BREB, PT and FAO-56 PM approaches totalled 561.3, 548.7 and 599.7 mm for the 2008 season and 543.6,

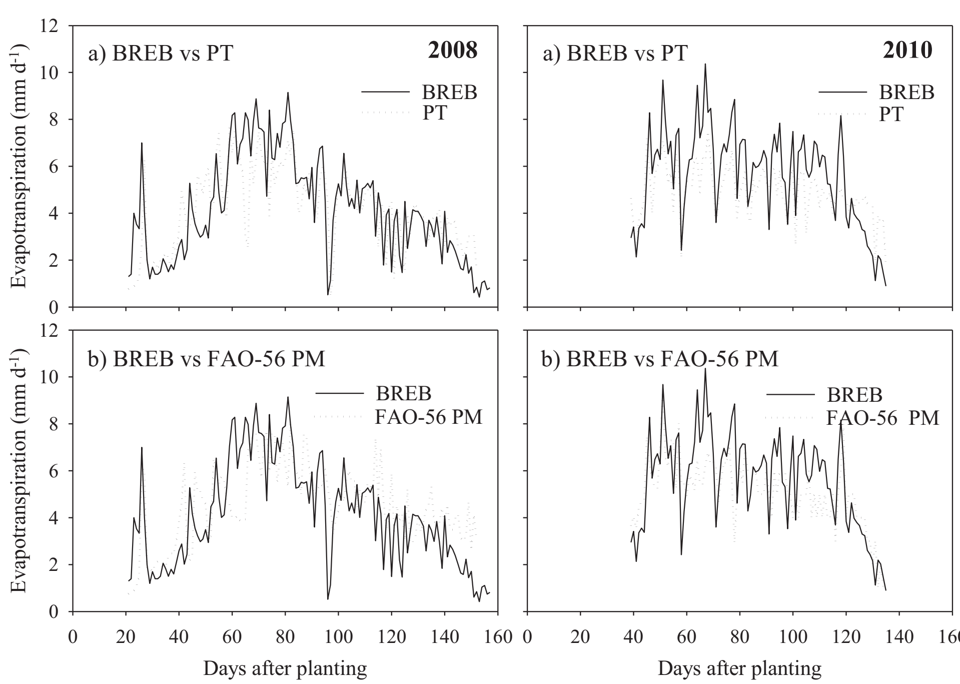

Fig. 2. Simulated daily evapotranspiration rates using (a) the Priestley–Taylor (PT) approach and (b) FAO-56 Penman–Monteith (PM) approach and measured with the Bowen ratio-energy balance (BREB) system for the full crop water requirements treatment (T_1) of the 2008 and the 2010 seasons.

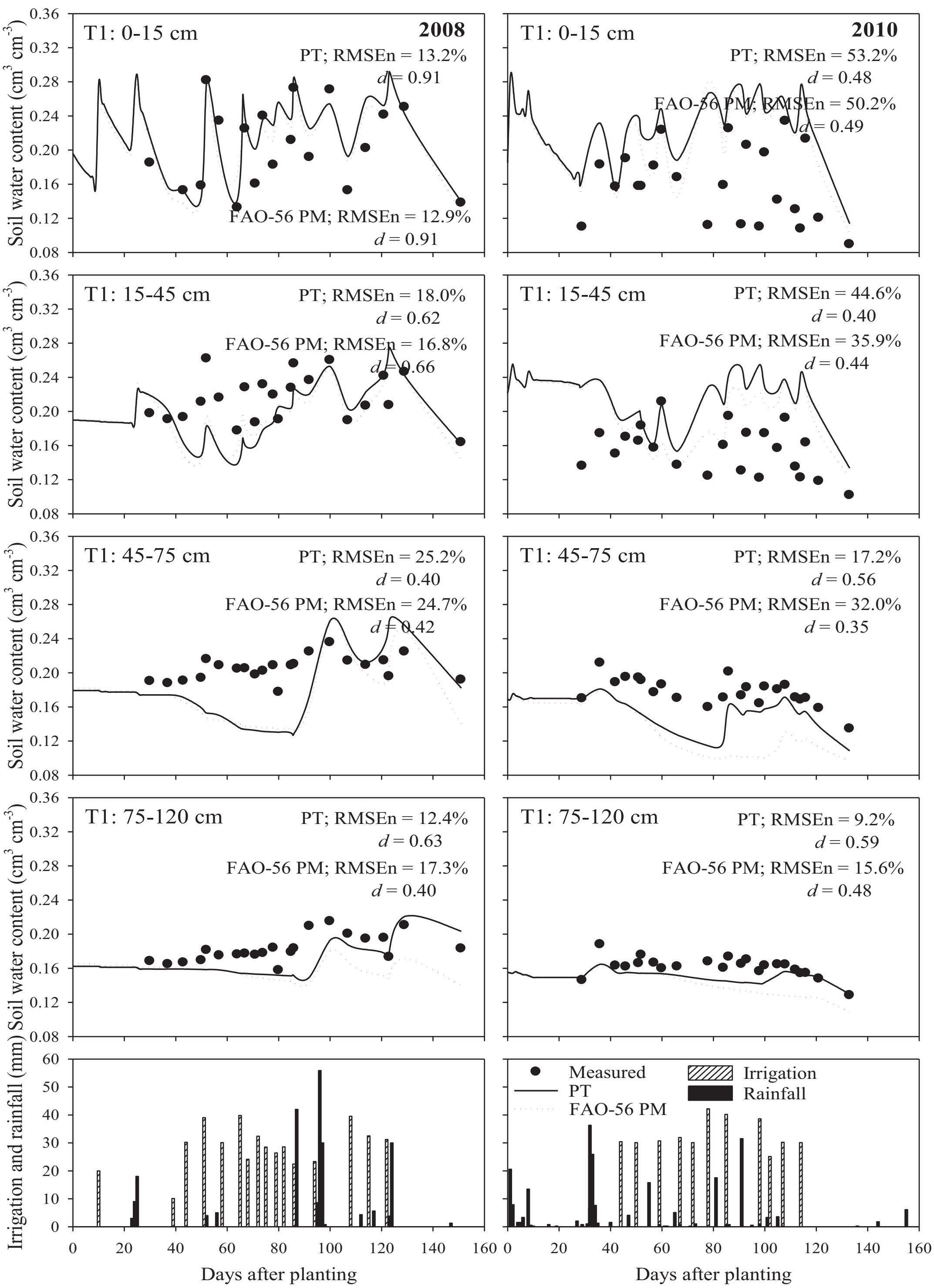

Fig. 3. Simulated soil water content using the CSM–CERES–Maize model with the Priestley–Taylor (PT) and FAO-56 Penman–Monteith (PM) approach, measured soil water content for different soil layers; and irrigation and rainfall events during the 2008 and 2010 growing periods for treatment T_1 (100% of full crop water requirements).

477.2 and 495.9 mm for the 2010 season. As can be seen in Fig. 1a and b, for 2008 the model using both ET approaches simulated cumulative ET that agreed well with the observed data from BREB when compared to 2010. However, both ET calculation approaches reproduced seasonal ET that was about 12% less when compared to the BREB measurements. The PT approach showed an underestimated value for the cumulative ET at 66 days after planting in 2008, whereas it underestimated the cumulative ET for the entire growing season in 2010 when compared to the BREB method. The FAO-56 PM approach slightly underestimated ET at 63 days after planting, but slightly overestimated the measured cumulative value at the end of the season in 2008, and it also underestimated the cumulative ET throughout the growing season in 2010 (Fig. 1). The FAO-56 PM approach had a closer agreement to the BREB method for the entire growing season than the PT approach in both 2008 and 2010 as indicated by the RMSEn and d-index values being 6.9% and 0.997 for the PT approach and 4.6% and 0.999 for the FAO-56 PM approach in the 2008 season. For the 2010 season, the RMSEn

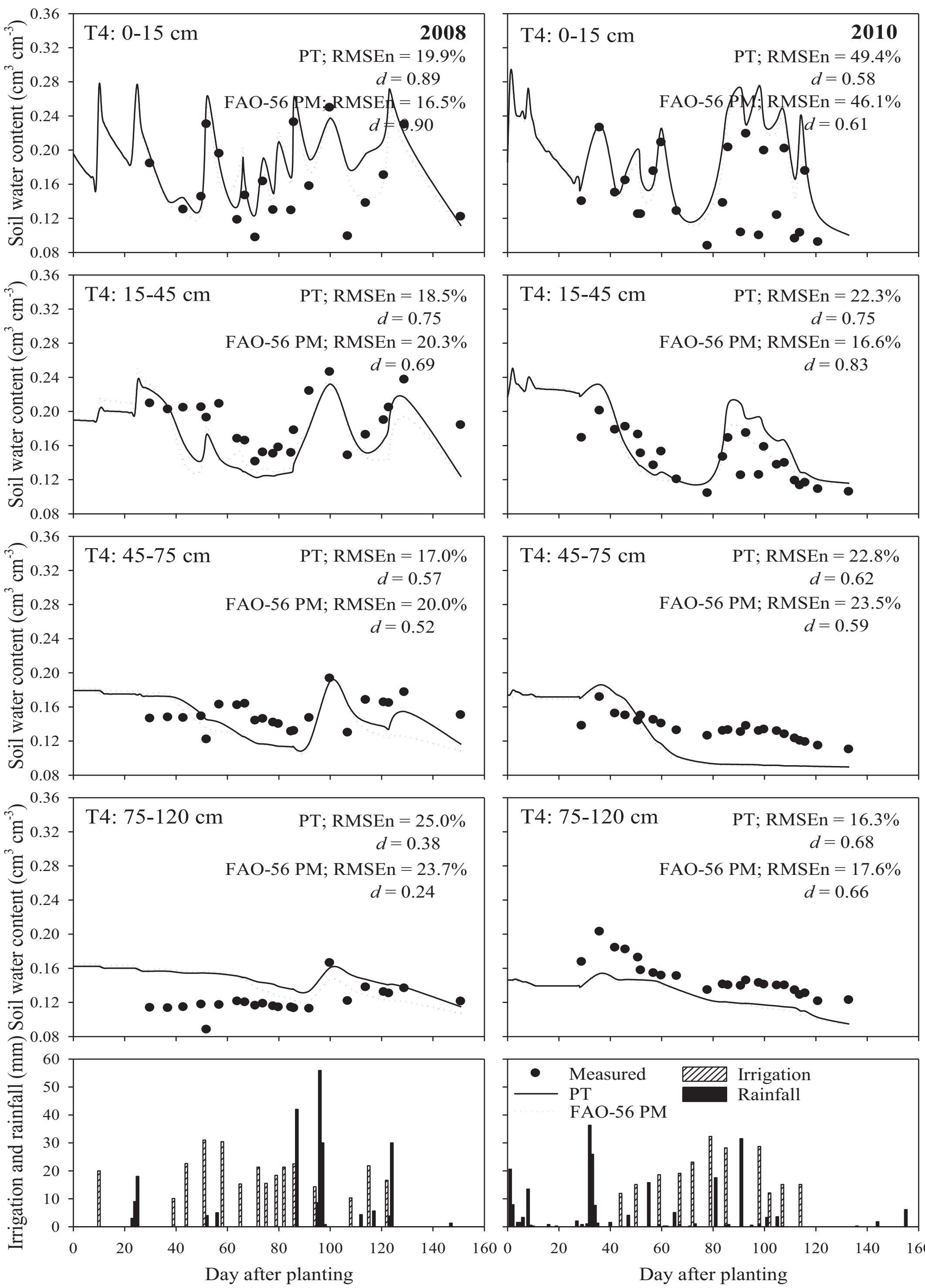

Fig. 4. Simulated soil water content using the CSM–CERES–Maize model with the Priestley–Taylor (PT) and FAO-56 Penman–Monteith (PM) approach, measured soil water content for different soil layers; and irrigation and rainfall events during the 2008 and 2010 growing periods for treatment T_4 (70% of full crop water requirements).

values were 15.4% for the PT and 9.0% for the FAO-56 PM and the *d*-index values were 0.973 and 0.991, respectively, for the PT and FAO-56 PM approach (Fig. 1a and b).

The simulated daily ET rates for both the PT and FAO-56 PM approach showed similar trends when compared to the observed daily ET rates based on BREB throughout the growing seasons, although some differences among the two approaches were observed (Fig. 2). The average daily ET rate for the entire growing season using the BREB, PT and FAO-56 PM methods was 4.25, 4.16 and 4.54 mm day^{-1} for 2008 and 5.60, 4.92 and 5.11 mm day^{-1} for 2010. Assuming that the BREB observed ET rates are correct, the daily ET rates based on both ET calculation approaches were within 12% as compared to the daily measured ET rates with BREB, with the simulated daily FAO-56 PM ET rates slightly more accurate than the daily PT rates. The RMSEn values based on the FAO-56 PM approach for the entire growing season of the daily ET rates were 37.9% for the 2008 season and 22.9% for the 2010 season and the *d*-index was 0.80 and 0.78 for the 2008 and 2010, respectively, while for the PT

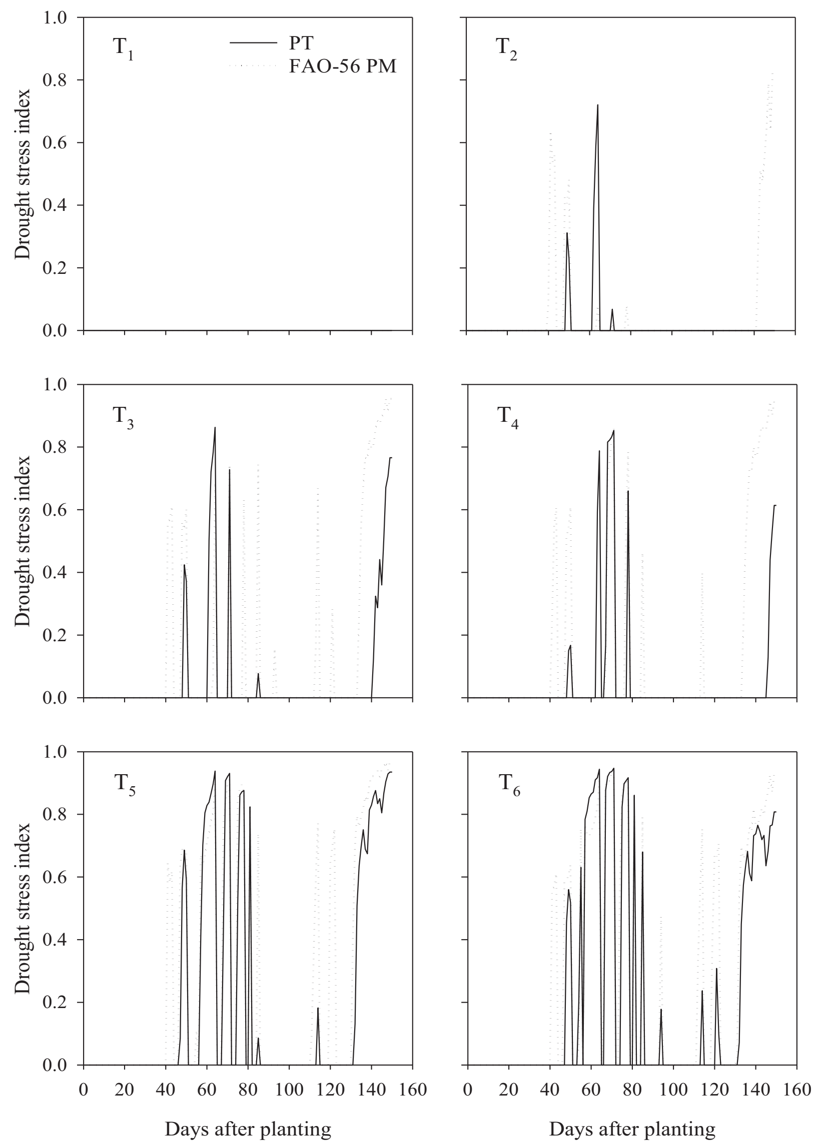

Fig. 5. Simulated drought stress index during the 2008 growing season for treatment T_1 (100%), T_2 (85%), T_3 (70%), T_4 (70%), T_5 (55%) and T_6 (40%) of full crop water requirements using the CSM–CERES–Maize model with Priestley–Taylor (PT) and FAO-56 Penman–Monteith (PM) ET approach.

approach, the RMSEn values were 42.8% in 2008 and 24.9% in 2010 and the *d*-index values were 0.74 and 0.78 for the 2008 and 2010 seasons, respectively (Fig. 2).

The visual comparison of Fig. 2 revealed that the dynamics of the daily PT ET and FAO-56 PM ET rates were similar to the measured ET rates early during the growing seasons, while the PT ET rates showed less daily fluctuation. However, later during the growing season there was a closer agreement between the daily PT and observed rate than between the FAO-56 PM and the observed rates (Fig. 2). The difference in patterns of the daily ET rates seems closely related to the requirement of additional weather data inputs. The daily PT ET rates had similar patterns to the daily minimum and maximum air temperature and especially solar radiation (data not shown). When using the FAO-56 PM approach, relative air humidity and wind speed played a part in determining the dynamic pattern of the daily ET rates.

3.3. Soil water content

To evaluate the performance of the soil water balance of the CSM–CERES–Maize model for different irrigation treatments, simulated soil water content with the two ET approaches was compared with the observed values for four soil depths: 0–15, 15–45, 45–75 and 75–120 cm. Although, soil water content was measured up to a depth of 200 cm, data are only presented for the top 120 cm depth as there was negligible soil water uptake between a soil depth of 120 and 200 cm.

The simulated and observed soil water content for the various depths of the soil profile are shown for the full crop water requirements treatment (T_1) and 70% irrigation treatment (T_4) (Figs. 3 and 4). Soil water content for the 0–15 cm soil depth for the PT showed a good agreement with the observed soil water content for all six irrigation treatments in 2008 and a moderate agreement for the 2010 season. The simulated soil water content was generally over-predicted for both the 2008 and 2010 seasons. The values for RMSEn for all six treatments ranged from 13.2 to 29.0% for the 2008 season and from 49.4 and 58.4% for the 2010 season. Their values for the *d*-index ranged from 0.75 to 0.92 for the 2008 season and from 0.48 to 0.58 for the 2010 seasons. For the 15–45 cm soil depth, the simulations were better than the 0–15 cm soil depth for both the 2008 and 2010 seasons, with values for RMSEn of both seasons that ranged from 12.7 to 44.6%, and the *d*-index that ranged from

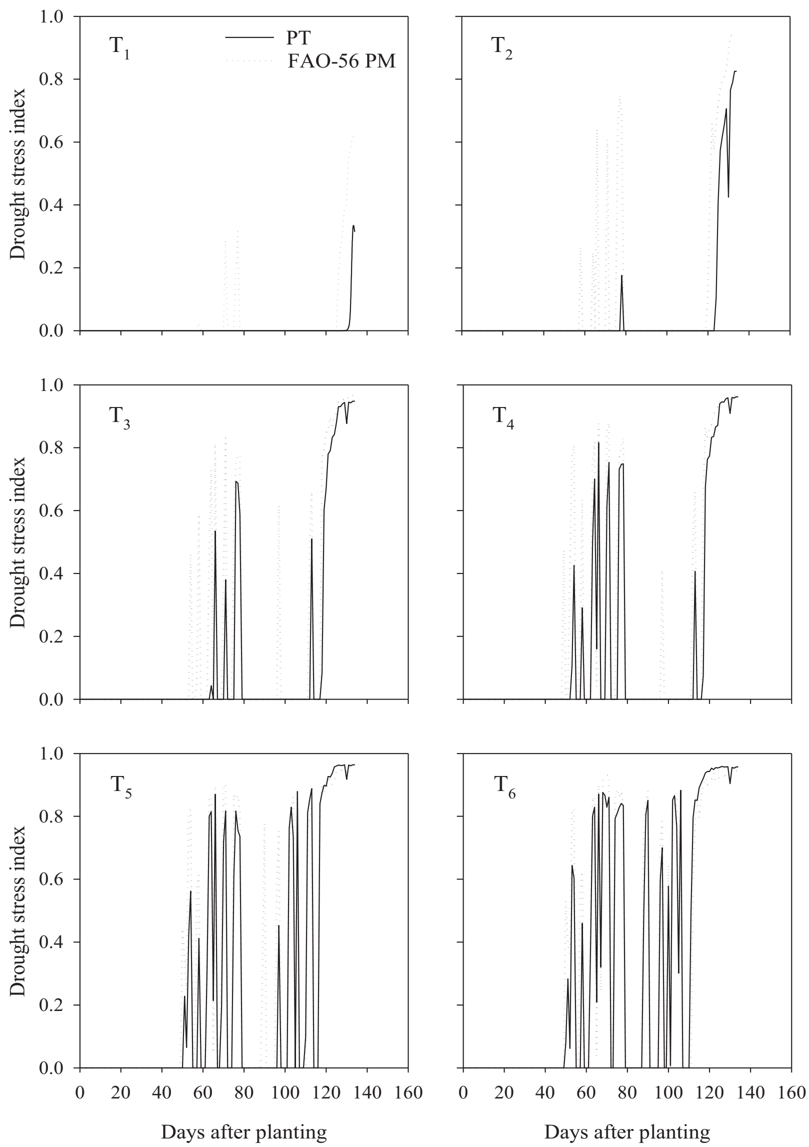

Fig. 6. Simulated drought stress index during the 2010 growing season for treatment T_1 (100%), T_2 (85%), T_3 (70%), T_4 (70%), T_5 (55%) and T_6 (40%) of full crop water requirements using the CSM–CERES–Maize model with Priestley–Taylor (PT) and FAO-56 Penman–Monteith (PM) ET approach.

0.43 to 0.92. Soil water content was also very well simulated for the 45–75 and 75–120 cm soil depths. The RMSEn for the two growing seasons ranged from 17.2 to 29.3% and from 9.2 to 25.0% for the 45–75 and 75–120 cm soil depths, respectively, while the *d*-index ranged from 0.39 to 0.82 for the 45–75 cm soil depth and from 0.46 to 0.89 for the 75–120 cm soil depth.

Soil water content simulated with the FAO-56 PM approach was similar to the soil water content simulated with the PT approach for all six irrigation regimes. In general, the model with FAO-56 PM approach performed better in simulating soil water content for the top two soil depths (0–15 and 15–45 cm soil depths) for all treatments as compared to the model with the PT approach, whereas the PT simulated slightly more accurate soil water content for deeper layer (45–75 and 75–120 cm) soil depths. The mean RMSEn values for the two growing seasons ranged from 12.9 to 50.3% for the 0–15 cm, 13.2 to 35.9% for the 15–45 cm, 18.9 to 32.0% for the 45–75 cm and 12.1 to 26.8% for the 75–120 cm soil depths. The values for the *d*-index ranged from 0.49 to 0.92, 0.44 to 0.92, 0.35 to 0.81 and 0.40 to 0.86 for the 0–15, 15–45, 45–75 and 75–120 cm soil depths, respectively (Figs. 3 and 4).

The experimental measurements showed that the fluctuation of soil water content for the full crop water requirements treatment (T_1) was large for the top 0–15 cm soil layer, moderate for the 15–45 cm soil layer and small for the two deeper layers (45–75 and 75–120 cm) (Fig. 3). The other irrigation treatments (T_2 to T_6) that had dryer regimes in comparison to T_1, had a high fluctuation in soil water content for the 0–15, 15–45 and 45–75 cm soil layers (Fig. 4). This could indicate that the maize roots penetrated deeper once the surface layer dried out as compared to the T_1 treatment. Likewise, the time span of cyclic variation was longer following more severe drought stress. Simulated soil water content with the CSM–CERES–Maize model using both ET calculation approaches was similar to the observed soil water content. In addition, the results also showed that the model was able to accurately simulate the measured changes in soil water content following irrigation and rainfall events (Figs. 3 and 4). Overall, the results based on the statistical indicators and the visual comparison time series data revealed that the CSM–CERES–Maize model using both the PT and FAO-56 PM approach satisfactorily predicted the soil water content under both non-limiting and water stress conditions.

3.4. Drought stress index

The drought stress index was used to assess the times of occurrence and severity of water stress during the cropping season. This index is one of several stress index outputs that is provided by the CSM–CERES–Maize model. The basic principle for determining the drought index is the comparison between potential transpiration or demand and potential root water uptake or plant extractable soil water. There are two drought stress indices in the CSM–CERES–Maize model: one for photosynthesis and the other for expansive plant growth. The drought stress interactions with crop phenological development are not simulated in the CSM–CERES–Maize model, while it has impact on the potential biomass production and LAI expansion of the day by decreasing in the same proportion as the transpiration. The drought index presented in this study is the drought stress index for plant growth.

As expected, the duration and the severity of drought stress tended to increase as the amount of water applied through irrigation declined (Figs. 5 and 6). In the 2008 growing season, the model using either the PT and FAO-56 PM approach did not simulate any drought stress during the growing season for the full crop water requirements treatment (T_1), indicating that the maize crop had an adequate water supply throughout the growing season, whereas the crop experienced drought stress in the other treatments (T_2 to T_6). For the 2010 season, the model using either the PT or FAO-56 PM approaches simulated the occurrence of drought stress during the growing season for all treatments but differed in severity, including the full crop water requirement treatment. As can be seen in Fig. 6, the PT and FAO-56 PM showed mild level of drought stress for the full crop water requirement treatment and both a longer duration and severity for the T_2 to T_6 treatments.

The CSM–CERES–Maize model using the FAO-56 PM approach simulated a drought stress index that was longer and more severe than the one based on the PT approach for ET calculation, in particular early and late during the growing season. Based on the FAO-56 PM approach, the cumulative simulated drought stress index for the entire growing season was 0, 9.5, 21.2, 21.7, 40.2 and 41.2 for the T_1, T_2, T_3, T_4, T_5 and T_6 treatments, respectively, for the 2008 season and 5.1, 14.8, 24.4, 28.4, 37.0 and 44.4 for the T_1 to T_6, respectively, for the 2010 season. Based on the PT approach for the 2008 season, the cumulative simulated drought stress index was 0, 2.8, 9.4, 8.2, 30.1 and 32.3 for the T_1, T_2, T_3, T_4, T_5 and T_6 treatments, respectively. For the 2010, the cumulative drought stress index was 0.7, 6.9, 17.3, 22.2, 32.5 and 42.6 for the T_1, T_2, T_3, T_4, T_5 and T_6, respectively. These differences were anticipated because the CSM–CERES–Maize model using the FAO-56 PM approach simulated higher daily ET rates than those derived from the PT approach. This agrees with the previous discussion that the remaining soil water content is very much related to ET. The cumulative simulated drought stress indicated that the model using both two ET calculation approaches simulated more drought stress for the 2010 than for the 2008 growing season for all irrigation treatments. This implied that maize was more exposed to drought stress in 2010 than in 2008 and could explain the lower measured grain yield and total final biomass for 2010 than for 2008 and could also partially explain the cause of the underestimation of simulated grain yield for 2010.

4. Conclusions

The simulated daily ET rates and seasonal ET using the FAO-56 PM approach had a closer agreement than those simulated with the PT approach when compared with measured ET by the BREB method. However, both ET calculation approaches reproduced daily and seasonal ET values within 12% as compared to the BREB measurements. There was a good agreement between simulated soil water content using both the PT and FAO-56 PM approach and observed soil water content over time for the different depths of the six irrigation treatments. Phenological development and grain yield using the PT and FAO-56 PM approach agreed well with the observed values, while final biomass was a moderate agreement for the various water regimes after calibrating to the full crop water requirement treatment. We can conclude that the CSM–CERES–Maize model using the two different ET approaches, PT and FAO-56 PM, was able to simulate responses to crop development and yield as well as ET and soil water content under different irrigation regimes in a semi–arid environment. The model with the FAO-56 PM approach performed better in grain yield, especially in 2008 and final biomass as compared to the observed data than the PT approach. Additionally, the FAO-56 PM approach for ETc estimation matched to BREB measured ETc better than the PT method. Therefore, it is recommended that when daily relative air humidity and wind speed observations are available, the FAO-56 PM approach should be used for the calculation of ET for the CSM–CERES–Maize model.

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