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THE DUAL CROP COEFFICIENT APPROACH: APPLICATION OF THE SIMDUALKC MODEL TO WINTER WHEAT IN NORTH CHINA PLAIN

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ABSTRACT The SIMDualKc model is a soil water balance and irrigation scheduling model that uses the dual crop coefficient approach for estimating crop evapotranspiration (ET_c). This approach separately considers soil evaporation and plant transpiration. The model uses a daily time-step and adjusts the crop coefficients to climate, crop density and height, and to soil water conditions. Three years of field experimental data relative to winter wheat were used for model calibration and validation. Data includes ET_c measured with lysimeters and soil water content observed with TDR in a silty loam soil. The calibration procedure consisted on adjusting the soil evaporation parameters, the basal crop coefficients (K_{cb}) and the soil water depletion fraction for no stress (p) for the soil water content simulated to match the observed values. Results show a good agreement between model predictions and field observations. For the calibration a regression coefficient b = 0.99 and an error $RMSE$ = 0.01 $m^3\ m^{-3}$ were obtained; for the validation b ranging 0.99-1.03 and $RMSE$ ranging 0.013-0.016 $m^3\ m^{-3}$ were computed. The simulated ET_c shows $RMSE$ = 0.75 mm d^{-1} for calibration and $RMSE$ ranging 0.51-0.79 mm d^{-1} for validation. Soil evaporation and crop transpiration average respectively 40.3 and 7.5 mm during the initial crop stage, 10 and 30 mm during the frozen soil period, 8.5 and 52.0 mm for the vegetative growth period, 7.0 and 190.8 mm for the mid season, and 16.5 and 75.0 mm for the end season. Soil evaporation represents 19% of ET_c.

Keywords: basal crop coefficients, evaporation coefficient, soil evaporation, crop transpiration, winter wheat.

INTRODUCTION Computing crop evapotranspiration using the dual crop coefficients approach allows dividing evapotranspiration into soil evaporation and plant transpiration because the crop coefficient then consists of a soil evaporation coefficient (K_e) and the basal crop coefficient (K_{cb}). Often, this approach produces more accurate results for daily ET_c estimation than using time average crop coefficients (Allen *et al.*, 1998; Allen, 2000; Allen *et al.*, 2005a). Liu and Pereira (2000) applied this methodology to North China Plain for a crop sequence of winter wheat-summer maize. Results of this study show that the dual crop coefficient approach is more appropriate to this crop sequence than the single time averaged crop coefficient. Many studies on the application of this methodology have been reported in recent years (e.g., Hunsaker *et al*. 2005; Er-Raki *et al*. 2007; Bodner *et al*. 2007; Liu and Luo 2010). Allen *et al*. (2005b) used the dual crop coefficient method to estimate evaporation and proposed some application extensions, *e.g.* separate prediction of evaporation from soil wetted by precipitation only.

Rolim *et al*. (2006) developed and tested a computational tool that computes crop evapotranspiration and performed soil water balance simulation based on the dual crop coefficient approach, the SimDualKc model. The model testing was performed for several experimental fields: in Portugal for maize; in Syria and Tunisia for wheat; and for cotton and winter wheat in Central Asia.

This paper refers to the calibration and validation of the SimDualKc model for irrigated winter wheat using three years of experimental data collected in the Daxing district, North China Plain.

MATERIALS AND METHODS

The SIMDualKc model The SIMDualK$_c$ model adopts the dual K_c approach to compute ET_c on a daily basis as proposed by Allen *et al.* (1998; 2005b):

$$ET_c = \left(K_s K_{cb} + K_e\right) ET_o \tag{1}$$

where ET_c is crop evapotranspiration [mm d^{-1}], K_{cb} is the basal crop coefficient [], K_e is the soil evaporation coefficient [], K_s is the stress coefficient [], and ET_o is the reference crop evapotranspiration [mm d^{-1}].

The soil water balance in the root zone, expressed in terms of depletion at the end of the day, is computed with a daily time step as (Allen *et al*., 1998; 2007):

$$D_{r,i} = D_{r,i-1} - (P - RO)_i - I_i - CR_i + ET_{c,i} + DP_i \tag{2}$$

where $D_{r,i}$ is the root zone depletion at the end of day i [mm], $D_{r,i-1}$ is the root zone depletion at the end of the previous day, i-1 [mm], P_i is the precipitation on day i [mm], RO_i is the runoff from the soil surface on day i [mm], I_i is the net irrigation depth on day i that infiltrates the soil [mm], CR_i is the capillary rise from the groundwater table on day i [mm], $ET_{c,i}$ is the crop evapotranspiration on day i [mm], and DP_i is the water loss out of the root zone by deep percolation on day i [mm]. In addition, the model performs a daily water balance of the soil evaporation layer according to the methodology proposed by Allen *et al*. (1998, 2007). Three extensions to evaporation calculation are used in the model to improve accuracy; the calculation of daily K_e values using the methodology updated by Allen *et al*. (2005b), including the estimation of the fraction of soil surface covered by vegetation (f_c), fraction of the soil surface wetted by irrigation (f_w), fraction of soil surface wetted and exposed to radiation (f_{ew}), and the determination of the evaporation reduction coefficient (K_r).

The model input data requirements includes:

- *Meteorological data:* concerning minimum and maximum temperature [ºC]; wind speed [m s^{-1}]; reference evapotranspiration [mm]; and effective precipitation [mm];

- *Soil data:* readily evaporable water [mm]; total evaporable water [mm]; and total available water [mm].
- *Crop data:* referring to dates of crop development stages, basal crop coefficients; maximum and minimum root depths [m]; maximum height [m] and soil water depletion fractions for no-stress;
- *Irrigation data:* the system type, options (no irrigation, irrigation to avoid water stress, deficit irrigation, variable irrigation depths according to an upper threshold of soil water storage, and simulate a defined irrigation schedule *i.e.* allows evaluating a given irrigation schedule), and water restrictions.

Field experiments and data collection The field experiments of winter wheat were carried out in the Irrigation Experiment Station of the China Institute of Water Resources and Hydropower Research (IWHR) at Daxing, south of Beijing (39º37´N latitude, 116º26´E longitude and 40.1 m altitude). Winter wheat is the main irrigated crop in the region. The climate in the experimental site is semiarid to sub-humid, with cold and dry winter and hot and humid summer, when monsoon rains occur. An automatic weather station is installed in the experimental station, which provides for measurements of air temperature, relative humidity, global and net radiation, wind speed at 2 m height, soil temperature at various depths, and precipitation.

The experiments were developed during three winter wheat growing seasons (2006-07, 2007-08 and 2008-09). The total precipitation was respectively 112.6, 208.6 and 114.6 mm. There were no significant differences in seasonal ET_o. A climatic characterization concerning the experimental site is presented in Fig. 1. The main soil in the experimental area is a silt loam and its hydraulic properties are presented in Table 1. Observations at Daxing have shown that the groundwater table is at 18 m depth and, therefore, capillary rise from the groundwater was not considered in the soil water balance calculations. However, during the 2007-08 irrigation season deep percolation occurred and it was computed using a parametric equation as proposed by Liu *et al*. (2006).

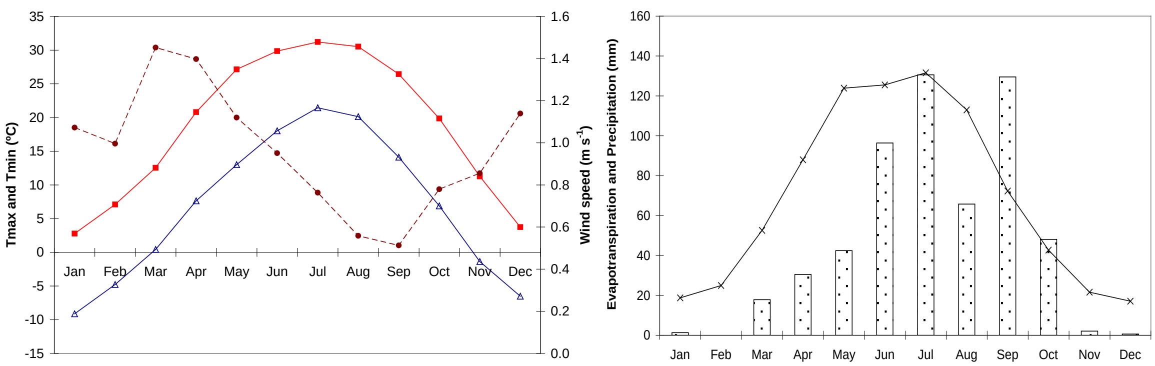

Figure 1. Climatic data of the Daxing meteorological station, North China Plain. On the left - average monthly maximum (—■—) and minimum (—△—) temperature, and wind speed (-•-); and on the right the monthly precipitation (⁝) and monthly reference evapotranspiration (ET_o) (—×—).

Table 1. Main soil hydraulic properties of Daxing experimental station.

Layer	Depth (m)	Saturated water content ($m^3\ m^{-3}$)	Field capacity ($m^3\ m^{-3}$)	Wilting point ($m^3\ m^{-3}$)
1	0.0-0.10	0.46	0.32	0.09

2	0.10-0.20	0.46	0.34	0.13
3	0.20-0.40	0.47	0.35	0.10
4	0.40-0.60	0.45	0.33	0.11
5	0.60-1.00	0.44	0.31	0.16

All the plots received a winter irrigation that refilled the soil reservoir. The irrigation in 2007-08 was postponed and the irrigation frequency was lower than the other two years due to pumping problems. The total irrigation depths in the three seasons are respectively 310 mm, 160 mm and 366 mm. The applied irrigation scheduling are described in Table 2.

Table 2. Irrigation treatments: applied water depths and dates.

Irrigation season	Date	Irrigation depth (mm)	Irrigation season	Date	Irrigation depth (mm)
2006-07	18/11	90	*2008-09*	18/11	60
	06/04	30		29/03	66
	21/04	60		20/04	70
	07/05	63		10/05	60
	04/06	67		18/05	50
2007-08	15/11	70		30/05	60
	05/04	30			
	03/06	60			

The soil water content was measured using a time-domain reflectometry (TDR) system TRIME®-T3/IPH, previously calibrated, for the entire root depth (1.0 m) with observations every 10 cm. Measurements were performed every 5 days. When precipitation or irrigation occurred the soil water content was also measured in the following day.

In the North China Plain region winter wheat crop is sowed in early October and reaped in middle June. The initial period, from planting to crop development, was divided into two sub-periods as a long frozen period occurred (around three months) in experiment station, the first from planting to soil frozen initiation; the second corresponding to the time, when the soil is frozen until crop reviving in Spring. The crop field data used for the simulations is summarized in Table 3. The crop evapotranspiration (ET_c) measurements were performed using a previously calibrated lysimeter which was placed in the middle of the wheat field. Further descriptions of the experimental station are given by Cai *et al*. (2009)

Table 3. Winter wheat crop growth stages for the 3 experimental years

	Crop seasons		
Crop growth stages	2006-07	2007-08	2008-09
Planting/Initiation	10-10	15-10	9-10
Frozen soil	1-12	01-12	10-12
Start rapid growth	15-3	10-3	01-3

Start mid-season	15-4	25-3	16-4
Start senescence/Maturity	25-5	25-5	25-5
End-season/Harvest	18-6	15-6	12-6

Model calibration and validation The calibration procedure consisted of adjusting the non-observed parameters (K_{cb}, *p*, *TEW*, *REW*, and initial soil water content), considering the range of values they can assume, in order to minimize the difference between observed and simulated available soil water; with this propose, data for the 2006-07 season was used. The validation consisted of using the values of these parameters for the two other experimental years (2007-08 and 2008-09) and verify the simulation performance. The initial set of parameter values introduced in the model were the ones suggested by Allen *et al*. (1998; 2005a).

Statistical indicators to assess model simulation To assess the accuracy of SimDualKc model predictions, qualitative and statistical strategies were used; the first by using a graphical representation of observed *vs* simulated soil water content (or ET_c values); the second is a regression forced to the origin between observed and simulated values (regression coefficient and determination coefficient). Additionally, the the root mean square error (*RMSE*) and the average absolute error (*AAE*) were computed. These indicators were used in former applications in North China (Liu *et al*., 1998; Cai *et al*., 2009).

RESULTS AND DISCUSSION Model simulations were initiated using the tabled values of K_{cb}, *p*, *TEW* and *REW* proposed by Allen *et al*. (1998) for the experimental conditions thus for wheat crop and silty loam soils. Therefore, the following values were used K_{cbini} = 0.15, K_{cbmid} = 1.10, K_{cbend} = 0.15 and *p* = 0.55. Tabled values of *REW* and *TEW* for silty loam soils range respectively 8 - 11 mm and 18-37 mm. After proper adjustment the following values were considered for the simulations: *REW* and *TEW* were respectively 11 and 35 mm; the initial depletion in the evaporable layer was 50 % of *TEW* for the 2006-07 and 2007-08 irrigation seasons and 0% for 2008-09. The initial depletion in the entire root depth was 50 % of *TAW* for 2006-07 and 2007-08 and 0% of *TAW* for 2008-09. Results presented in Table 4 show that the K_{cbini}, K_{cbmid} and *p* adjusted values are in agreement with those presented in Allen *et al*. (1998, 2007). $K_{cb\ end}$ higher probably because the crop is harvested earlier than it is usual.

Soil water content The results from comparing the observed and the simulated soil water content (m^3m^{-3}) for the calibration and the two validation years of the wheat crop are presented in Fig. 2. It shows that the field observed values cover a large range of soil water content values. The computed goodness of fitting indicators are presented in Table 5. The results show that for all cases the regression coefficient is close to 1.0; the determination coefficients varies between 0.80 and 0.93, thus indicating that predicted values are close to the observed ones. The estimation of error indicators show a good agreement between observed and simulated values: the *RMSE* values range 0.010 and 0.016 m^3m^{-3}; the *AAE* are lower than 0.013 m^3m^{-3}.

Table 4. Trials base information referring to the characteristics of winter wheat crop, Daxing, North China Plain.

	Crop season		
	2006-07	2007-08	2008-09
$K_{cb\ ini}$	0.15	0.15	0.15
$K_{cb\ off}$	0.5	0.5	0.4
$K_{cb\ mid}$	1.2	1.2	1.2
$K_{cb\ end}$	0.4	0.4	0.4
p_{ini}	0.65	0.65	0.65
p_{dev}	0.65	0.65	0.65
p_{mid}	0.55	0.55	0.55
p_{end}	0.6	0.6	0.6

Table 5. Indicators of goodness of fitting relative to the model testing for the wheat crop, Daxing, North China Plain

	b	R^2	*RMSE* ($m^3\ m^{-3}$)	*AAE* ($m^3\ m^{-3}$)
2006-07 (calibration)	0.99	0.93	0.010	0.009
2007-08 (validation)	0.99	0.80	0.016	0.013
2008-09 (validation)	1.03	0.80	0.013	0.010
All experiments	*1.0*	*0.88*	*0.013*	*0.010*

Results show that the SIMDualKc model adequately predicts the soil water content during the wheat growing season and are in agreement with the results of a former study on wheat by Liu and Pereira (2000).

Crop evapotranspiration Since field observations were performed for wheat *ET*, in addition to the comparison described above, a comparison between daily observed and model simulated *ET* was also performed (Fig. 3 and Table 6). Results show a good agreement between observed and simulated daily *ET* values, with a regression coefficient ranging 0.90-1.05 and a high coefficient of determination (0.81-0.91). Results show a small overestimation of the model simulations during the calibration year (2006-07) and a underestimation during one of the validation years (2008-09). The estimated errors are relatively small, with *RMSE* ranging 0.51 to 0.79 mm d^{-1} and *AAE* ranging 0.42 to 0.63 mm d^{-1}. When all data for the three experimental years are used for the same comparison it results *b* close to 1.0 and R^2 = 0.85; the estimated errors *RMSE* and *AAE* are then 0.68 and 0.53 mm d^{-1} respectively.

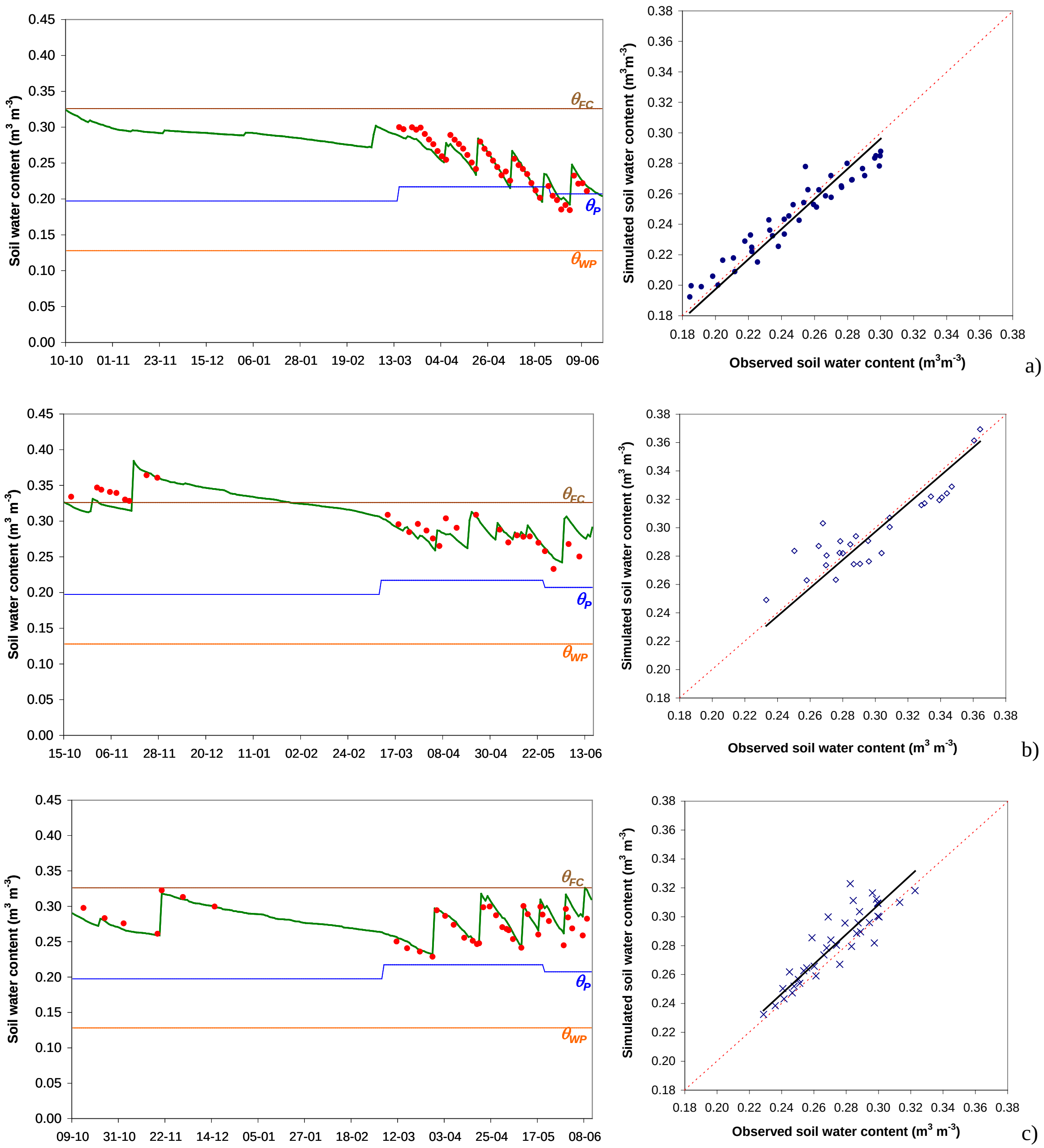

Figure 2. Comparison between simulated and observed soil water content for the wheat crop: (a) 2006-07 (calibration), (b) 2007-08 (validation), and (c) 2008-09 (validation), Daxing, North China Plain. On the left, the simulated soil water content and observed values (•) (curves θ_{FC} , θ_{WP} and θ_p represent soil moisture at field capacity, wilting point, and when depletion equals the fraction *p*, respectively); on the right the regressions.

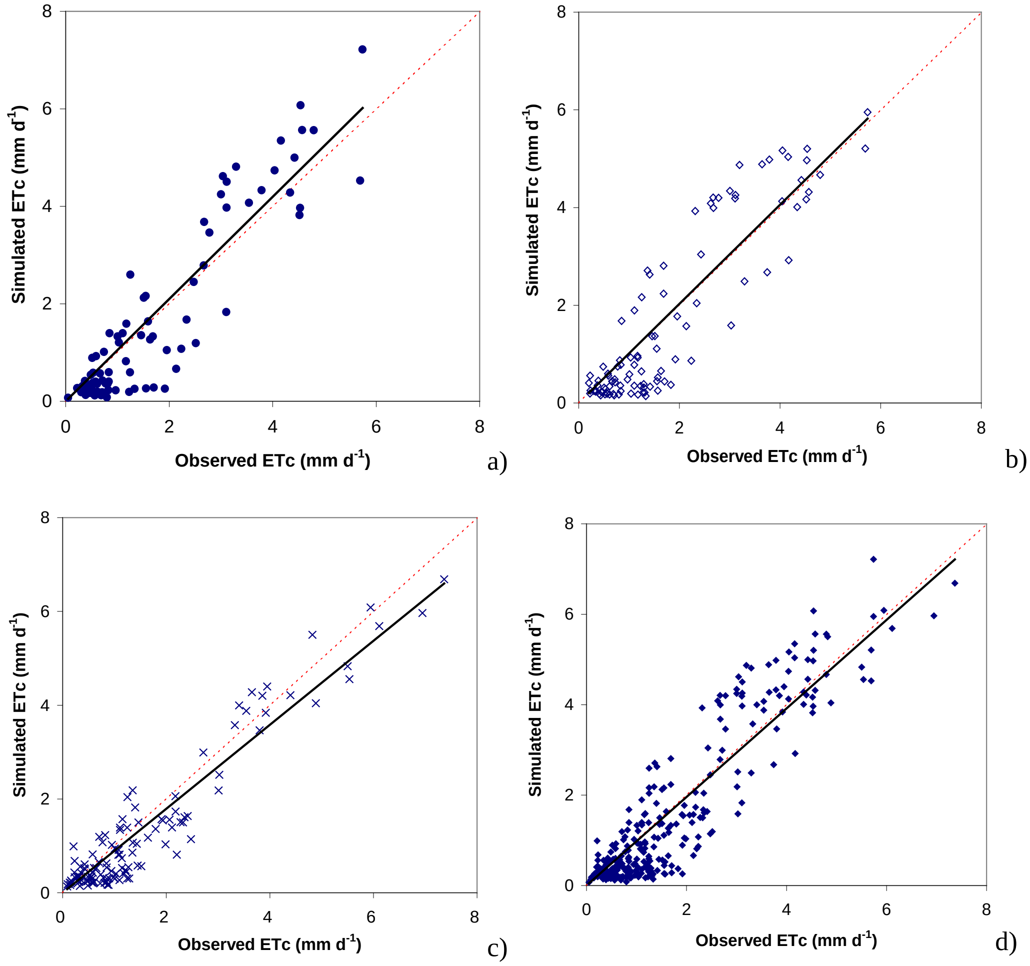

Figure 3. Regression between observed and computed daily wheat evapotranspiration: a) 2006-07 (calibration); b) 2007-08 (validation); c) 2008-09 (validation); d) all experiments considered, Daxing, North China Plain.

Table 6. Indicators of goodness of fitting relative to the comparison between lysimeter measured and SimDualKc simulated wheat evapotranspiration, Daxing, North China Plain

	b	R^2	*RMSE* (mm d^{-1})	*AAE* (mm d^{-1})
2006-07 (calibration)	1.05	0.85	0.75	0.59
2007-08 (validation)	1.01	0.81	0.79	0.63
2008-09 (validation)	0.90	0.91	0.51	0.42
All experiments	*0.98*	*0.85*	*0.68*	*0.53*

As previously mentioned, the SimDualKc model allows the computation of the two ET_c components, soil evaporation (*E*, mm) and plant transpiration (*T*, mm). Table 7 presents the results for *E* and *T* for each season and crop growth stage. They show for all crop seasons that *E* is the main ET_c component during the initial crop growth stage, representing 81 to 89 % of the ET_c for that period. During the frozen soil season it decreases to 16 to 27%; during the vegetative growth period *E* decreases to a minimum of

6 % of ET_c in the case of 2008-09 and a maximum of 22% of ET_c in the 2007-08 experiment. For the mid-season period *E* is negligible when compared to *T* for all cases. For the end-season period the importance of *E* increases ranging 11 to 28%. The latter is due to a late irrigation. The total ET_c was 438.5, 421.9 and 446.4 mm respectively for 2006-07, 2007-08 and 2008-09 seasons; thus evaporation represents 17 to 22%.

Table 7**.** Evaporation (*E*), transpiration (*T*) and evaporation significance relative to crop evapotranspiration (E/ET_c),for each development stage of the wheat crop, Daxing, North China Plain

	E (mm)			*T* (mm)			E/ET_c (%)		
Crop growth stages	06-07	07-08	08-09	06-07	07-08	08-09	06-07	07-08	08-09
Initial	33.3	35.8	51.8	7.6	5.8	9.2	81.3	88.6	85.8
Frozen soil	11.1	5.6	10.1	31.0	30.2	27.8	26.5	15.7	26.6
Development	14.7	6.3	4.6	59.7	22.8	73.5	19.7	21.8	5.9
Mid season	6.0	8.5	6.4	182.9	215.6	173.9	3.2	3.8	3.5
End season	9.7	14.2	25.5	82.4	78.2	64.3	10.5	15.3	28.4

CONCLUSIONS The SIMDualK_c model was successfully calibrated and validated using observations of the soil water content and of the wheat evapotranspiration performed at Daxing in North China Plain during the period 2006-2009. Results for the soil water content showed regression coefficients near 1.0 and high determination coefficients ranging 0.80 to 0.93 and small errors. For the case of the model testing using the *ET* observation results and considering data for all the experimental years, the regression coefficient relating simulated and observed values is close to 1.0 and the determination coefficient is high (0.85). The estimated errors refer to good results, with $RMSE$ = 0.68 mm d^{-1} and AAE = 0.53 mm d^{-1}. The studies therefore produced good estimates of the basal crop coefficients and depletion fractions for no stress that may be able to support farmers' advice as well as to predict *ET* and irrigation requirements for planning and environmental studies.

The SIMDualK_c model represents a step further in the soil water balance simulation tools, making use of a more precise and suitable methodology to support improving water productivity and water savings in the North China Plain. The model has shown to be able to simulate the processes of evaporation and transpiration in every growth season, which can be used to support soil and irrigation managements. Thus, after calibration a study of the two components of the ET_c was performed. Results show that the ratio of evaporation to evapotranspiration (E/ET_c) for the entire growth season was 17.1%, 16.7% and 22.0% respectively for 2006-07, 2007-08 and 2008-09 experiments.

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