A simple method using climatic variables to estimate canopy temperature, sensible and latent heat fluxes in a winter wheat field on the North China Plain

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Abstract:

Estimation of evapotranspiration from a crop field is of great importance for detecting crop water status and proper irrigation scheduling. The Penman–Monteith equation is widely viewed as the best method to estimate evapotranspiration but it requires canopy resistance, which is very difficult to determine in practice. This paper presents a simple method simplified from the Penman–Monteith equation for estimating canopy temperature ($T_c$). The proposed method is a biophysically-sound extended version of that proposed by Todorovic. The estimated canopy temperature is used to calculate sensible heat flux, and then latent heat flux is calculated as the residual of the surface energy balance. An eddy covariance (EC) system and an infrared thermometer (IRT) were installed in an irrigated winter wheat field on the North China Plain in 2004 and 2005, to measure $T_c$, and sensible and latent heat fluxes were used to test the modified Todorovic model (MTD). The results indicate that the original Todorovic model (TD) severely underestimates $T_c$ and sensible heat flux, and hence severely overestimates the latent heat flux. However, the MTD model has good capability for estimating $T_c$, and gives acceptable results for latent heat flux at both half-hourly and daily scales. The MTD model results also agreed well with the evapotranspiration calculated from the measured $T_c$.

KEY WORDS surface energy balance; canopy–air temperature difference; vapour pressure deficit; evapotranspiration

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INTRODUCTION

The quantification of evapotranspiration between vegetation surface and atmosphere plays an important role in many environmental issues including water management, agricultural production, climatic change, ecological applications, and policymaking (Batra et al., 2006). In agricultural practices, evapotranspiration is a key factor for scheduling proper irrigation, detecting crop water status, improving water use efficiency, and for saving limited water resources, especially in arid and semiarid regions.

Significant advances in recent decades have been made in the understanding of the dominant factors which control crop evapotranspiration. Penman (1948) initially established an equation incorporating all the weather variables which have direct effects upon the evapotranspiration process. Based on Penman’s equation, Monteith (1965) presented the famous Penman–Monteith (PM) equation, which was widely used for estimating evapotranspiration. Of all the variables that the PM equation requires, canopy resistance ($r_c$) is the most difficult to determine.

There are two types of methods commonly used to determine $r_c$. The first one is aimed at simulating the stomatal conductance (reciprocal of resistance) at leaf scale, and then up-scaling it to canopy scale. The simulation of leaf stomatal conductance has received much attention in the past few decades. Jarvis (1976) proposed an empirically multiplicative model to describe the response of leaf stomata to changes in environmental factors. Ball et al. (1987) developed a semi-empirical stomatal model in which the mathematical relation between relative humidity over a leaf surface, atmospheric CO$_2$ concentration and photosynthetic rate was incorporated under conditions of ample water supply. Collatz et al. (1991), Leuning (1995) and Yu et al. (2002) calculated stomatal conductance by coupling transpiration and photosynthesis. More recently, Tuzet et al. (2003) and Yu et al. (2007), among many others, also take the effect of leaf water potential into account. These stomatal conductance models at leaf scale can be used to determine canopy resistance by up-scaling based on appropriate approaches (De Pury and Faquhar, 1997; Cox et al., 1998). However, these models require many parameters which cannot be measured easily. In agricultural practice, these complicated models are normally not used. On the other hand, the discussion about whether to use a constant or a variable stomatal resistance is still going on (Todorovic, 1999; Lecina et al., 2003; Allen et al., 2006; Katerji and Rana, 2006; Pauwels and Samson, 2006; Perez et al., 2006). However, it is necessary to parameterize the variable $r_c$ because of its changes with meteorological factors.

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(solar radiation, air temperature, CO₂ concentration, wind speed, available soil water supply, and vegetation cover), with time of the day and day of the year. Katerji and Rana (2006) investigated the evapotranspiration of six irrigated crops under Mediterranean climate and showed that the use of variable \( r_c \) has significant advantage over constant \( r_c \) when they were used to estimate evapotranspiration using the PM equation.

Another method is the so-called climatic method for calculating canopy resistance. Katerji and Perrier (1983) first posed a semi-empirical method to determine \( r_c \) by means of a linearly correlating \( r_c \) to climatic resistance as defined by Monteith (1965). Rana et al. (1994), Rana and Katerji (1998), Perez et al. (2006), and Ortega-Farias et al. (2006) presented different functions to derive \( r_c \) by environmental variables. This kind of method, called ‘climatic’, needs to predetermine at least two coefficients prior to use. Todorovic (1999) introduced a method called ‘climatic’, needs to predetermine at least two coefficients prior to use. Todorovic (1999) introduced a climatic-variables-based model (TD) to estimate canopy resistance, which needs no parameterization and no new parameter. But TD model application may fail under irrigated conditions in semi-arid regions. Another drawback of the TD model comes from introducing a new concept, the ‘resistance for heat flow’ from a nonsaturated surface, which does not exist in reality (Allen et al., 2006).

Using a big leaf concept, if the value of either canopy temperature or canopy resistance is known, the evapotranspiration can be determined in terms of the PM equation. Jackson et al. (1981) and Silva and Rao (2005), among many others, described the relationship between canopy resistance and canopy temperature. Jones (1999) also investigated the relationship between canopy temperature and canopy resistance based on the ‘wet’ and ‘dry’ leaves assumption. Pereira (2004) summarized the coherence of the Penman–Monteith equation and Priestley–Taylor (PT) equation. The results of all this research indicate that parameterizations for canopy resistance, canopy temperature, PT parameter, and Bowen ratio are essentially equivalent, and any one can be determined from any of the others when a ‘big leaf’ concept is used. In fact, canopy temperature is the result of canopy energy balance, and hence surface temperature can be used as a measure of the difference between actual transpiration (for dry leaves) and potential transpiration (for wet leaves). Numerous researchers have used canopy temperature to quantify the status of crop water stress and supply potential aid to irrigation scheduling and water management (Idso et al., 1981; Jackson et al., 1981; Nielsen and Gardner, 1987; Nielsen, 1990; Alves and Pereira, 2000; Alderfasi and Nielsen, 2001; Orta et al., 2003; Silva and Rao, 2005).

Using the coherence of canopy temperature and canopy resistance for estimating evapotranspiration, this paper proposes a very simple formula (MTD model) to estimate canopy temperature, and hence the sensible and latent heat fluxes. Another objective of this paper is to test the MTD model and compare the results with those using the TD model using IRT measured canopy temperature and sensible and latent heat fluxes measured by eddy covariance (EC) in an irrigated winter wheat field in a semiarid region of the North China Plain.

THEORY

The energy balance equation above a vegetative surface, without considering the effects of advection on evapotranspiration, is given by

\[
R_n - G = \lambda ET + H
\]

(1)

where \( R_n (W m^{-2}) \) is the solar net radiation, \( G (W m^{-2}) \) the soil heat flux, \( \lambda ET (W m^{-2}) \) the latent heat flux, and \( H (W m^{-2}) \) the sensible heat flux.

Adopting the so-called ‘resistance concept’ between the vegetation surface and reference height, sensible heat flux can be computed by

\[
H = \rho C_p \frac{T_c - T_a}{r_a}
\]

(2)

where \( \rho (kg m^{-3}) \) is the mean air density at constant pressure, \( C_p (J kg^{-1}°C^{-1}) \) the specific heat of air, \( r_a (s m^{-1}) \) is the aerodynamic resistance, and \( T_c (°C) \) canopy temperature and air temperature, respectively.

The calculation of the latent heat flux based on the PM equation (Monteith, 1965; Allen et al., 1998) can be written as

\[
\lambda ET = \frac{\Delta (R_n - G) + \rho C_p D/r_a}{\Delta + \gamma (1 + r_c/r_a)}
\]

(3)

where \( \Delta (kPa °C^{-1}) \) is the slope of the temperature–saturation vapour pressure relationship, \( D (kPa) \) the vapour pressure deficit, \( \gamma (kPa °C^{-1}) \) is the psychrometric constant, and \( r_c (s m^{-1}) \) is the canopy resistance.

Combining Equations (1)–(3), the canopy–air temperature difference, \( T_c - T_a \), can be computed by

\[
T_c - T_a = \frac{R_n - G}{\rho C_p} \frac{\gamma r_a (r_a + r_c) - Dr_a}{\Delta + \gamma r_a + \gamma r_c}
\]

(4)

Under the conditions of water–vapour saturated vegetative surface, evapotranspiration activity was not affected by vegetal factors, i.e. \( r_c = 0 \). This circumstance is commonly referred to as potential evapotranspiration \( (\lambda ET_p) \), and Equation (4) can be change to the following form:

\[
T_c - T_a = \frac{R_n - G}{\rho C_p} \frac{\gamma r_a}{\Delta + \gamma}
\]

(5)

From Equations (4)–(5), we obtain

\[
t = T_c - T_{cp} = \frac{(\Delta + \gamma)(\Delta \gamma r_c + \gamma Dr_c)}{(\Delta + \gamma)}
\]

(6)
where $t$ is the difference between actual canopy temperature and canopy temperature in wet conditions, and $r_i$ is an ‘isothermal resistance’ defined by Monteith (1965) and is also called climatological resistance in some references:

$$r_i = \frac{\rho C_P D}{\gamma (R_n - G)} \tag{7}$$

For convenience, the last item at the right side of Equation (6) is defined as $C$, i.e.,

$$C = \frac{\Delta \frac{1}{D} + \frac{1}{\gamma r_i}}{\frac{1}{\Delta r_a} + \frac{1}{\gamma r_a}} \tag{8}$$

and then, Equation (6) changes to

$$t = \frac{\gamma}{\Delta + \gamma} D C \tag{9}$$

Todorovic (1999) proposed the following formula to estimate $t$

$$t = \frac{\gamma}{\Delta + \gamma} D \tag{10}$$

Comparing Equations (10) and (9), one can see that Todorovic assumes the value of $C$ is always 1. But actually, $C$ is a function of climatological variables, aerodynamic resistance and canopy resistance.

Then, using the same parameterization as Leuning (1995) for the response of stomatal conductance to VPD, one gets for the response of $t$ to vapour pressure deficit $D$

$$t = \gamma \frac{1}{D + \gamma} D (1 + D/D_0) \tag{11}$$

where $D_0$ is a parameter which accounts for the response of $t$ to air humidity deficit (i.e. VPD). The parameter $D_0$ is widely used in simulating the response of stomatal conductance to VPD (Leuning, 1995; Yu et al., 2002; Isaac et al., 2004; Wang et al., 2004). In the North China Plain, Yu et al. (2002) reported that for winter wheat crop the suitable value of $D_0$ could be taken as 1.5 kPa which is used in the current research. Equation (11) (MTD model) is a physically sound extended version of Equation (10) since it includes a parameter which possibly has its physical meaning in reflecting the response of canopy temperature to vapour pressure deficit.

According to the PM equation, potential evapotranspiration is

$$\lambda ET_p = \frac{\Delta (R_n - G) + \rho C_P D/r_a}{\Delta + \gamma} \tag{12}$$

In terms of canopy surface energy balance equation (Equation (1)), the sensible heat flux in the case of as potential evapotranspiration ($H_p$, W m$^{-2}$) can be obtained

$$H_p = R_n - G - \lambda ET_p \tag{13}$$

Then the canopy temperature ($T_{cp}^\circ C$) in the potential evapotranspiration state can be computed inversely by

$$T_{cp} = \frac{r_a H_p}{\rho C_p} + T_a \tag{14}$$

and then, actual canopy temperature, $T_c$, can be computed by

$$T_c = T_{cp} + t \tag{15}$$

According to the relationship between $r_c$ and $T_c$ (Jackson et al., 1981; Silva and Rao, 2005), $r_c$ can be computed by

$$r_c = \frac{\gamma r_a (R_n - G)/(\rho C_p) - (\Delta + \gamma)(T_c - T_a) - D}{\gamma[(T_c - T_a) - r_a (R_n - G)/(\rho C_p)]} r_a \tag{16}$$

Finally, aerodynamic resistance between the top of the plant and a reference level $z$ above the canopy was calculated by (Thom and Oliver, 1977)

$$r_a = \frac{4.72 \left( \ln \frac{z - d}{z_0} \right)^2}{1 + 0.54u} \tag{17}$$

where $z$ (m) is the reference height, $d$ (m) the displacement height, $z_0$ the roughness length (m), and $u$ the wind speed (m s$^{-1}$). The terms $z_0$ and $d$ can be represented as functions of the crop height ($h$, m). In the current study, $d = 0.56 h$ and $z_0 = 0.13 h$ were assumed basing on Legg and Long (1975).

Substituting Equation (15) into (16), the value of $r_c$ can be determined and the latent heat flux can be estimated based on the PM equation (3); or substituting Equation (15) into Equation (2), the sensible heat flux, $H_c$, can be estimated, and then the latent heat flux, $\lambda ET$, can be calculated as the residual of energy balance Equation (1).

MATERIAL AND METHODS

Experiments were conducted in an irrigated winter wheat field at the Yucheng Comprehensive Experiment Station (36°57’ N, 116°36’ E, 28 m above a.s.l) of Chinese Academy of Sciences, located in the North China Plain. Measurements were made at the centre of a 300 m × 300 m field of winter wheat (Triticum aestivum L.). The soil type is silt loam in the North China Plan (NCP). The site has a temperate monsoon climate with rainfall concentrated in summer and rarely occurring through the wheat growth period during winter and spring. The wheat plants were sown in north–south rows with regular sowing density. Winter wheat variety was Zixuan 1. The crop was flood irrigated, and fertilizer was amply supplied.

Sensible and latent heat fluxes were measured with an eddy covariance system installed 2-1 m above ground level. The system consisted of a fast response, open path infrared gas analyzer, which measures water and carbon dioxide concentrations (IRGA; Model LI-7500, LI-COR, Inc., Lincoln, NE) and a three-dimensional sonic anemometer (Model CSAT3, Campbell Scientific Inc., Logan UT). Data were recorded with a data-logger (CR23X Campbell Scientific Inc.) and the sampling frequency was 20 Hz for all channels. The Webb correction was applied and sonic temperature was corrected.
for humidity measured with the Licor. The half-hourly average values were calculated and used for the analysis. A net radiometer (CNR1, Kipp & Zonen, USA) was installed 2.1 m above the ground to measure downward and reflected shortwave and long-wave radiation. Air temperature and relative humidity were measured with temperature/humidity probes (HMP45C, Vaisala, USA). Wind speed was measured using an anemometer (A100R, Vector, UK). Two soil heat flux plates (HFP01SC, Hukseflux) were set at a depth of 0-10 m at the row and aisle position.

Canopy surface temperature was measured by an infrared thermometer (IRT) installed on a bracket of the eddy covariance system with a 45° angle from the horizontal, detecting radiation in the 8–14 μm wave bands (Minolta/Land Cyclops Compact 3, USA). To avoid the soil being viewed, the viewing direction of IRT was set in a direction perpendicular to the crop row, i.e. with an east–west direction. Calibration of the IRT was performed prior to the measuring period using a commercial black body surface. Canopy temperature was measured every minute and the half-hourly average values were recorded.

During the growing season, crop height and leaf area index (LAI) were measured every 5 days by harvesting 20 plants and measuring leaf area by LI-3100 (LI-COR Inc., Lincoln) within a plot of 1 m² area, and plant height was measured. To make IRT viewed canopy temperature reliable, the canopy temperature data in the periods when LAI > 2.5 m² m⁻² (DOY 85–136 in both experimental years) were chosen for analysis. Flux data taken by eddy covariance were automatically corrected by the WPL (Webb–Pearman–Leuning) method.

RESULTS

Canopy temperature

The top panel of Figure 1 shows the diurnal dynamics of canopy temperature viewed by IRT, original Todorovic (TD) and modified Todorovic (MTD) models. The data presented in Figure 1 are from local time 0600h to 1800h with half-hourly intervals during the period between DOY 124 and DOY 130, 2004. It is obvious that the MTD model had a better performance than the original one, especially at 2 h after noon when air temperature and VPD were high (the bottom panel in Figure 1). The MTD model results agreed well with the IRT viewed canopy temperatures, but the TD model underestimated the canopy temperature by 0–3.5°C around the noon. The results demonstrated that the TD model might be suitable for estimating evapotranspiration in humid regions where air VPD was not too high, even around noon, and crop growth can be supported by natural precipitation. However, the North China Plain is a semi-arid region whose climate is characterized as dry, windy and less precipitation. Compared with the TD model, the MTD model just added a new item, 1 + D/D₀, to the TD model. When air VPD tends to 0, and the added term tends to 1, the MTD model is nearly the same as the TD model. With an increase in air VPD, the newly added item is greater than 1, and the estimated canopy temperature could be enhanced by D/D₀ times.

Figure 2 presents a comparison between half-hourly values of canopy temperature estimated by TD and by MTD models and IRT viewed canopy temperature in daytime from 0600h to 1800h during the period between DOY 85 and DOY 136 in both 2004 and 2005. In this period, for wheat canopy LAI values over 2.5, the
canopy can be viewed as fully closed, and IRT viewed canopy temperature data are credible. In both years, the MTD model works significantly better than the TD model. The slope of linear regression improved from 0.84 to 0.94 in 2004 and from 0.75 to 0.84 in 2005. Major improvements derived from the times when viewed canopy temperature is high, generally with high air VPD.

The coefficient of determination ($R^2$) between estimated sensible heat flux, compared with the original model. The MTD model decreased from 1 to 0.91 and lower than that of the TD model. In 2005, the $R^2$ is 0.51, and $\sigma$ value also decreased from 0.72, but $\delta$ improved from 86.47 W m$^{-2}$ to 28.95 W m$^{-2}$, and $R^2$ value also increased from 0.32 to 0.47. These results indicate that the MTD model has a significant improvement over the TD model, and the MTD simulations fit well with observed sensible heat flux by the EC instrument.

### Sensible heat flux

In order to make reasonable comparisons between EC-measured sensible heat flux data and model-estimated data, the slope of linear regression ($\sigma$), the intercept of linear regression ($\delta$) and $R^2$ are used as the main indicators to evaluate the model’s predictive performance. The closer the value of $\sigma$ is to 1 and smaller the value of $\delta$ is, the better the model’s predictive performance, and the higher the $R$ value, the better the model’s performance.

Figure 3 shows a comparison between half-hourly values of $H$ estimated by the TD and MTD models and EC-measured $H$ in year 2004. For the TD model, the model presents an unacceptable estimation of $H$. The value of $\sigma$ is 0.87, and $R^2$ value is 0.25. The main reason for this poor predictive performance is that the TD model underestimated canopy temperature and hence underestimated the sensible heat flux. The MTD model presented a significant improvement in the estimation of sensible heat flux, compared with the original model. With the MTD model, the $\sigma$ value increased to 0.99 and $R^2$ value to 0.58, the $\delta$ value also decreased from 42.34 to 25.13 W m$^{-2}$.

### Latent heat flux

Figure 4 shows that the comparison between half-hourly values of $\lambda ET$ estimated by the TD and MTD models and the EC-measured $\lambda ET$ in years 2004 and 2005. In 2004, $\sigma$ for the TD model is 1.51, and $R^2$ is 0.82. The $\sigma$ for the MTD model is 1.08, which is 0.47 lower than that of the TD model. In 2005, $\sigma$ for the TD model is 1.70, and $R^2$ is 0.86. The $\sigma$ for the MTD model is 1.04, a 0.64 reduction compared with the TD model.
Figure 3. Comparison between half-hourly measured sensible heat flux (H) and sensible heat flux estimated by the original Todorovic model (H_{TD}) and the modified Todorovic model (H_{MTD}) in 2004 and 2005.

Figure 4. Comparison between half-hourly measured latent heat flux (ET) and sensible heat flux estimated by the original Todorovic model (ET_{TD}) and the modified Todorovic model (ET_{MTD}) in 2004 and 2005.
This demonstrated that, due to underestimated canopy temperature and sensible heat flux, the original TD model overestimated $\lambda ET$ by about 60%. The MTD model gave acceptable results compared with the EC-observed latent heat flux.

The eddy covariance technique is widely used to observe the latent heat flux between vegetation surface and atmosphere. A common problem with this technique is the energy imbalance that often occurs (Wilson et al., 2002; Li et al., 2005; Li and Yu, 2007). In order to test the performance of the proposed MTD model, the latent heat flux inversely calculated from the IRT-viewed canopy temperature based on the Penman–Monteith equation was used as the ‘true’ latent heat flux to compare with the model simulation results. Figure 5 shows the comparison between $\lambda ET$ estimated by the two models and the inversely derived $\lambda ET$ from the IRT-viewed canopy temperature. The $\sigma$ values in both 2004 and 2005 are very close to 1, and $R^2$ values in both years are satisfactory.

**Daily evapotranspiration**

The daily values of evapotranspiration $ET$ (mm day$^{-1}$) estimated by the TD and MTD models are calculated from the sum of the half-hourly values estimated by the same model, from 0600h to 1800h in each day.

Figure 6 presents the comparison between $ET$ daily values estimated by the two models and measured in the same period. In 2004, the $\sigma$ value is 1.59 for the TD model and 1.09 for the MTD model. $R^2$ decreased slightly, from 0.83 to 0.80. In 2005, the $\sigma$ value is 2.15 for TD model and 1.15 for MTD model. Unfortunately the $R^2$ value decreased from 0.84 to 0.58, however, the $\delta$ value also decreased from 1.55 mm day$^{-1}$ to 0.37 mm day$^{-1}$. Based on comprehensive consideration, the MTD model is better than the TD model in simulating the daily $ET$.

Similarly to analysis on a half-hourly scale, in this section, daily $ET$ derived inversely from canopy temperature is compared with those calculated by the two models. The year 2004 results show $\sigma$ values of 1.68 and 0.99 for the TD and MTD models, respectively. The 2005 results give $\sigma$ values of 1.68 and 0.99 for the TD and MTD models, respectively. $R^2$ does not change significantly in 2004 (0.84 versus 0.70) but is a little lower in 2005 (0.84 versus 0.70) (Figure 7).

**DISCUSSION AND CONCLUSION**

In this paper, a modified Todorovic model is proposed to compare with IRT-viewed canopy temperature and the EC measured sensible and latent heat fluxes. The results indicate that the MTD model gives significant improvement over the TD model in estimating canopy…
Figure 6. Comparison between measured evapotranspiration (Daily ET) and evapotranspiration estimated by the original Todorovic model (Daily ET_TD) and the modified Todorovic model (Daily ET_MTD) at daily scale in 2004 and 2005.

Figure 7. Comparison between daily inversely derived evapotranspiration (Daily ET_Tc) from IRT-viewed canopy temperature and evapotranspiration estimated by the original Todorovic model (Daily ET_TD) and the modified Todorovic model (Daily ET_MTD) in 2004 and 2005.
temperature and sensible heat flux. The latent heat flux estimated using the MTD model is better than that using the TD model at both half-hourly and daily scales. A comparison between model simulations and the latent heat flux inversely calculated from IRT-viewed canopy temperature was also made. These results also demonstrated that the MTD model performed better than the TD model. The values of root mean square error (RMSE) for simulated $T_c$, $H$ and $\lambda ET$ using the modified Todorovic model presented significant improvement over the original Todorovic model. This indicates that the simulation results for $T_c$, $H$ and $\lambda ET$ are closer to the observations. However, both $R^2$ and RMSE values for the sensible heat flux simulations were not very strong. Empirical calculations of displacement and roughness lengths may be one possible reason for this poor performance.

The key contribution of this paper is that a new parameter, $D_0$, which possibly has its physical meaning in reflecting the response of canopy temperature to vapour pressure deficit, is added to the original Todorovic model. As is known, canopy temperature has a close feedback relationship with canopy conductance (resistance) (Jackson et al., 1981; Silva and Rao, 2005), therefore, introducing this parameter $D_0$ (and the item $1 + D/D_0$) to describe the response of canopy temperature seems reasonable. The newly added term, $1 + D/D_0$, gives an implicit but effective adjustment to the original model. It modifies the linearity of the relationship between potential and actual canopy temperatures proposed by Todorovic (1999) to a quadratic expression and produces more realistic values of canopy temperature. When air VPD approaches zero, the added term is 1 and the modified model is equivalent to the original model. With increasing air VPD, the new item is greater than 1, and estimated canopy temperature is improved by $D/D_0$ times. The value of $D_0$ in this paper is simply fixed at 1.5 kPa, which has been proven to be effective in an irrigated field on the North China Plain. What can be imagined is that the value of $D_0$ can vary with crops and climatic conditions. More work should investigate the variations of $D_0$ with different crops and in different regions.

The MTD model proposed here can estimate the canopy temperature from standard climatic variables with high accuracy given that the parameter $D_0$, introduced from biophysical knowledge, was well determined for a crop in a specific area prior to use. This method can easily be used to calculate crop water stress index (CWSI) (Idso et al., 1981; Jackson et al., 1981) to detect crop water stress status and to aid agricultural irrigation scheduling and water management. Another potential utility would be to assimilate remotely sensed surface temperature using the MTD model based on modern data assimilation techniques, such as ensemble Kalman filter and particle filter to improve the estimation of evapotranspiration at regional scales. These combined utilities might have the potential to enhance predictive performance for crop and ecological model applications.

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