A Novel Approach for the Simulation of Reference Evapotranspiration and Its Partitioning

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Abstract: To estimate the irrigation volume required for agriculture and improve water resources utilization efficiency, it is essential to obtain an estimate of reference evapotranspiration ($ET_0$) and its components (e.g., reference transpiration, $T_0$, and reference soil evaporation, $E_0$). This study updated a soil-plant-atmosphere continuum (SPAC) evapotranspiration model and its associated components to obtain a reference-based SPAC model of reference evapotranspiration ($R-SPAC$), and it applied the model to an agricultural ecosystem. Model simulations of mean hourly $ET_0$ were benchmarked against those of the Penman-Monteith method by the Food and Agriculture Organization (FAO-PM) throughout the growing season. The resulting good correlation obtained ($R^2 = 0.96$, agreement index, $I = 0.98$, root-mean-square deviation (RMSD) = 0.05 mm h$^{-1}$) validated the accuracy of the R-SPAC model. Sensitivity analysis was used to explore uncertainties and errors for $ET_0$, $T_0$, and $E_0$ caused by input variables. The results showed that net radiation and shortwave radiation at the study site were the main drivers of $ET_0$ for both the FAO-PM and R-SPAC models. The study showed that the proposed R-SPAC model can be used for predicting $ET_0$ and for exploring interactions between climate, crop type, and soil in determining evapotranspiration under various future environment conditions.

Keywords: reference evapotranspiration; numerical modeling; evaporation and transpiration; energy balance; diurnal variations; seasonal variations

1. Introduction

Quantitative estimations of reference evapotranspiration ($ET_0$) are a fundamental requirement for irrigation management and planning within agriculture and for water resources management [1–3]. Actual evapotranspiration ($ET_a$) is influenced by multiple factors, including those associated with the atmosphere, land surface conditions (e.g., crop type), and soil moisture, among which soil moisture and surface characteristics are the most difficult to quantify [4–6]. As an approach to overcome this challenge, the Food and Agriculture Organization (FAO) recommends the use of reference evapotranspiration ($ET_0$), which represents evapotranspiration from actively growing green grass under adequate watering with fixed crop height, albedo, and surface resistance conditions of 0.12 m, 0.23, and 70 S m$^{-1}$, respectively [1]. $ET_0$ is applied to represent the effects of atmospheric conditions and acts as a reference from which to estimate crop evapotranspiration ($ET_c$) and potential evapotranspiration ($ET_p$) from field to regional scales [3,7–9].

Many approaches exist for estimating $ET_0$ [10–14], including those based on a single meteorological variable, such as air temperature [15], solar radiation [16], or mass transfer [17] using pan evaporation. However, the aforementioned methods are case-study specific and therefore are not generalized. The Penman-Monteith method by the FAO (FAO-PM) has been proposed to be the single standard for determining $ET_0$ [1,4], as it has been considered to provide the most accurate simulations. The FAO-PM model is able to represent a larger range of physical processes that control ET and is thereby able to
simulate the differences in heat, mass, and momentum transfer among different surface components such as plants and the soil surface. However, a shortcoming of the FAO-PM model is its treatment of the soil surface as a uniform layer, and thereby its inability to quantify the differences in ET contribution between plants and soil. Many multi-source models have been developed to understand energy partitioning between sources and the routing of sensible and latent heat [7,18–21]. Two-source models have been shown to be capable of reasonably estimating ET and its components under different climate and vegetation conditions [22–25]. The FAO PM and updated Shuttle Worth–Wallace dual-source models [18] have been shown to be capable of estimating \( \text{ET}_0 \) and its components. However, these models do not fully consider the balance between energy and radiation between the soil surface and reference plants, unlike the two-source energy balance (TSEB) model [22,26], whose performance can be validated through the use of total ET, other forms of heat flux, and surface temperature. However, the TSEB method requires directional measurements of radiation temperature, thereby limiting the potential for its use, and there is no representation of stomatal control of transpiration in the TSEB model, which restricts further study of different crop types (e.g., crop evapotranspiration). To date, few studies were conducted to estimate \( \text{ET}_0 \) and its components under a reference crop catchment.

Many previous studies have shown evapotranspiration to be useful as an integrated climatic function for understanding ecosystem dynamics under climate change [27]. However, factors controlling \( \text{ET}_0 \) are site specific and therefore remain unclear. The aims of the present study were to (1) develop a novel approach for simulating and parameterizing \( \text{ET}_0 \); (2) validate the developed model by application of an agriculture catchment; and (3) describe the factors controlling seasonal variations in \( \text{ET}_0 \).

2. Materials and Methods
2.1. An Updated Reference-SPAC (R-SPAC) Model for \( \text{ET}_0 \)

The present study updated the SPAC model developed by Wang and Yamanaka [28] to partition energy/water fluxes. Originally, the SPAC model was used to simulate the actual evapotranspiration (\( \text{ET}_a \)) and partition \( \text{ET}_a \) into transpiration (\( T \)) and evaporation (\( E \)). The existing SPAC model achieved good performance in partitioning ET in the humid grasslands of Japan [28], arid and semi-arid grassland in Inner Mongolia [21], the typical ecosystem of the Heihe River Basin [25], and Alpine Meadow in Tibetan Plateau [29]. Therefore, we used the main equations of the SPAC model [28] and applied it on the reference land surface in this study. Figure 1 shows the modeling scheme adopted in the present study. Equation (1) and Equation (2) show the calculations for the balance between energy and radiation in the reference canopy of the plants and at the surface of the ground, respectively:

\[
R_{nV} = (1 - f_V)[0.77 S_d + L_d + \sigma T_G^4 - 2\sigma T_L^4] = H_{V0} + lT_0 \tag{1}
\]

\[
R_{nG} = f_V[0.77 S_d + L_d] + (1 - f_V)\sigma T_L^4 - \sigma T_G^4 = G_0 + H_{G0} + lE_0 \tag{2}
\]

where \( R_{nV} \) represents the net radiation of the canopy of the reference plants (W m\(^{-2}\)), \( T_0 \) represents the reference transpiration flux (kg m\(^{-2}\) s\(^{-1}\)), \( H_{V0} \) represents the sensible flux of heat from the canopy of the reference plants (W m\(^{-2}\)), \( S_d \) is the short-wave radiation in a downward direction (W m\(^{-2}\)), \( f_V \) denotes the permittivity of the canopy of plants, \( L_d \) is the long-wave radiation in a downward direction (W m\(^{-2}\)), \( \sigma \) is 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} \text{ representing the Stefan–Boltzmann constant}, \( T_G \) represents the temperature of the surface of the ground (°C), \( R_{nG} \) represents the surface of the ground net radiation (W m\(^{-2}\)), \( T_L \) represents the temperature of leaves (°C), \( G_0 \) represents the heat flux of the ground (W m\(^{-2}\)), \( H_{G0} \) represents the flux of sensible heat of the surface of the ground (W m\(^{-2}\)), and \( E_0 \) represents the flux of evaporation (kg m\(^{-2}\) s\(^{-1}\)). The reference crop per unit of area total flux is derived by adding those of the canopy of the plants and surface of the ground:

\[
R_n = R_{nV} + R_{nG}, H_0 = H_{V0} + H_{G0}, \text{ and } l(\text{ET}_0) = l(E_0 + T_0). \tag{3}
\]
Figure 1. An updated reference: soil-plant-atmosphere continuum (R-SPAC) model for estimating reference evapotranspiration and its components, updated from Wang and Yamanaka, 2014 [28]. All symbols used are defined in the text.

The value of \( f_V \) is derived as a function of LAI:

\[
  f_V = 1 - \tanh(c_{LAI} \cdot \text{LAI})
\]  

where \( C_{LAI} \) represents a constant, which is taken to be unity. The reference surface albedo values in the current study are 0.23 for both the canopy of the plants and surface of the surface. The leaf area index (LAI) was assumed to be 1 (m\(^2\) m\(^{-2}\)).

The \( T_0 \) and \( E_0 \) can be derived by:

\[
  T_0 = \rho_a [q_{sat}(T_L) - q_a] / (r_{aV} + r_c)
\]

\[
  E_0 = \rho_a [q_{sat}(T_G) - q_a] / (r_{aG} + r_{ss})
\]

where \( q_{sat}(T_G) \) and \( q_{sat}(T_L) \) represent specific humidity values at saturation for the surface of the ground and leaf and temperature, respectively (kg kg\(^{-1}\)), \( q_a \) represents the humidity of the air (kg kg\(^{-1}\)), and \( r_c \) and \( r_{ss} \) are the reference canopy resistance due to plant stomata and the resistance of the surface soil values, respectively, with both having constant values (70 s m\(^{-1}\)).

Similarly, the \( H_{V0} \) and \( H_{G0} \) are given as:

\[
  H_{V0} = c_p \rho_a (T_L - T_a) / r_{aV}
\]

\[
  H_{G0} = c_p \rho_a (T_G - T_a) / r_{aG}
\]

where \( r_{aV} \) represents aerodynamic resistance for the reference canopy of the plants (s m\(^{-1}\)) and \( r_{aG} \) represents resistance to aerodynamics posed by the surface of the ground (s m\(^{-1}\)).

\( r_{aV} \) and \( r_{aG} \) are calculated as [30]:

\[
  r_{aV} = \ln \left( \frac{z_m - d_0}{z_{0V}} \right) \ln \left( \frac{z_h - d_0}{z_{0hV}} \right) / k^2 u
\]

\[
  r_{aG} = \ln \left( \frac{z_m}{z_{0mG}} \right) \ln \left( \frac{z_h}{z_{0hV}} \right) / k^2
\]

where \( z_m \) is height from which measurements of the speed of wind were taken, which is regarded as 2 m in the current study, \( d_0 \) represents the zero-plane height of displacement (m) and is taken to equal \( 0.666 \times Z_V \) in the current study, where \( Z_V \) represents reference plant height, which is equal to 1.2 m in the current study, \( z_{0mV} \) represents the roughness
length controlling the transfer of momentum above the reference canopy of the plants (m), and it is taken to be 0.123 × Zv in the current study. Zh represents the height at which measurements of temperature and humidity were taken, and it is regarded as 2 m in the current study. z0hiv is the length of roughness controlling the transfer of heat and vapor above the reference canopy of the plants (m), and it is taken to be 0.1 × z0mV in the current study. k represents the von Karman’s constant, which is regarded to be 0.41 in the current study. u represents the speed of wind (m s⁻¹), z0mG represents the length of roughness controlling the transfer of momentum above the surface of the ground (m), and it is regarded to be 10⁻⁴ in the current study, and z0Gc represents the length of roughness controlling the transfer of vapor and heat vapor above the surface of the ground (m), and it is taken to be 0.1 × z0mG in the current study.

G0 is calculated using the heat conduction law of Fourier as:

\[ G_0 = \lambda_{soil} (T_G - T_{ss}) / z_{soil} \]  

(11)

where \( \lambda_{soil} \) represents the conductivity of heat at the soil surface (W m⁻¹ K⁻¹) and \( T_{ss} \) represents the temperature of the soil surface (°C) at depth \( Z_{soil} \) (m). \( \lambda_{soil} \) is assumed to be constant at 0.4 in the present study for the sake of simplicity, as it shows less sensitivity to variations in soil moisture in well-watered agricultural catchments.

2.2. Numerical Solution for ET0 by the R-SPAC Model

The Newton-Raphson (NR) scheme can be used as a robust method of obtaining a solution with an improved convergence rate [31], and it has seen application for diagnostically resolving energy balance equations [32]. Introduction of the NR iteration scheme aimed to solve Equations (1) and (2) simultaneously for \( T_L \) and \( T_G \), respectively. The provision of observed values of \( L_d, u, S_d, T_a, P, h_a, \) and \( T_{soil} \) allows the values of \( T_L \) and \( T_G \) to be derived for the calculation of all energy/water fluxes.

By rearranging Equations (1) and (2) with \( x \) equal to \( T_L \) and \( y \) equal to \( T_G \), the following can be derived:

\[ F(x, y) = (1 - f_V) \cdot 0.77S_d + L_d + \sigma y^4 - 2(1 - f_V)\sigma x^4 - c_p\rho_a(x - T_a) / r_w - \rho_a q_{sat}(x) - q_a / (r_w + 70) \]  

(12)

\[ G(x, y) = f_V \cdot 0.77S_d + L_d] + (1 - f_V)\sigma x^4 - \lambda (y - T_{soil}) / z_{soil} - \sigma y^4 - c_p\rho_a(y - T_a) / r_w - \rho_a q_{sat}(y) - q_a / (r_w + 70). \]  

(13)

Close solutions of \( y \) and \( x \) that are more similar to actual values can be derived by iteratively solving the equation below:

\[ \begin{pmatrix} \Delta x \\ \Delta y \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix}^{−1} \begin{pmatrix} −F \\ −G \end{pmatrix} \]  

(14)

\[ a = \partial F / \partial x = -8(1 - f_V)\sigma x_i^3 - c_p\rho_a / r_w - \rho_a \frac{0.622}{P} \frac{1}{R_w(x_i + 273.16)} e_{sat}(x_i) / (r_w + 70) \]  

(15)

\[ b = \partial F / \partial y = 4(1 - f_V)\sigma y_i^3 \]  

(16)

\[ c = \partial G / \partial x = 4(1 - f_V)\sigma x_i^3 \]  

(17)

\[ d = \partial G / \partial y = -4\sigma y_i^3 - \lambda / z_{soil} - c_p\rho_a / r_w - \rho_a \frac{0.622}{P} \frac{1}{R_w(y_i + 273.16)} e_{sat}(y_i) / (r_w + 70) \]  

(18)

where \( \Delta x \) equals \( x_{i+1} - x_i \) and \( \Delta y \) equals \( y_{i+1} - y_i \), in which \( i \) represents the iteration number, \( R_w \) represents the water vapor gas constant, and \( e_{sat}(x_i) \) or \( e_{sat}(y_i) \) are the vapor pressures at saturation at temperatures \( x_i \) or \( y_i \), respectively. Iterations are halted when absolute values of \( \Delta y \) and \( \Delta x \) are below 0.0001.

Equations (12) and (13) exclude a correction in the stability of the atmosphere to avoid the procedure used in the iteration from becoming increasingly complicated. Thankfully, since the model excludes the use of known values of \( T_G \) and \( T_L \), the calculated flux values
are likely to have a lower sensitivity to the stability of the atmosphere, whereas calculated temperature values may show some affect.

2.3. The FAO-PM Model for Estimating $ET_0$

The FAO-PM method has proposed to be the accepted approach for determining $ET_0$ [1], and it is also used in the present study (Equation (19)):

$$ET_0 = \frac{0.408 \Delta (R_n - G) + \gamma \left( \frac{900}{T_a - 273} \right) U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 U_2)}$$ (19)

where $R_n$ represents crop surface net radiation (MJ m$^{-2}$ day$^{-1}$), $G$ represents the density of the flux of soil heat (MJ m$^{-2}$ day$^{-1}$), $T_a$ represents the mean daily temperature of air at a 2 m height ($^\circ$C), $U_2$ represents wind speed at a height of 2 m, $e_s$ represents pressure of vapor at saturation (kPa), $e_a$ is actual pressure of vapor (kPa), $e_s - e_a$ represents the deficit in the vapor pressure at saturation (kPa), $\Delta$ is the pressure curve of slope vapor (kPa $^\circ$C$^{-1}$), and $\gamma$ represents the psychometric constant (kPa $^\circ$C$^{-1}$).

2.4. An Analysis of the Sensitivity of the R-SPAC Model

The present study conducted a sensitivity analysis to better understand the relationship between variations in simulations of $ET_0$ by the R-SPAC and variations in model input factors using the method proposed by Wang and Yamanaka [28]. The sensitivity coefficient ($S_i$) can be determined as:

$$S_i = \frac{\partial O}{\partial p_i} = \frac{O}{p_i}$$ (20)

2.5. Model Validation Dataset

An actual meteorological and flux dataset were applied to the R-SPAC model, and simulations of $ET_0$ and actual $ET_a$ were validated against that by the FAO-PM method and measurements by eddy covariance. These meteorological and flux datasets were obtained for Daman sites (38° 51’ N, 100° 22’ E, 1550 m) in an arid cropland of spring maize and artificial oasis in the mid reaches of the Heihe River Catchment, Zhangye, China, which forms a part of the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) program [33]. The study site has a mean annual air temperature and precipitation of approximately 7.4 $^\circ$C and 128.7 mm, respectively from 1961 to 2010, and a mean annual pan evaporation of 2002.5 mm. A field with an area about 13 ha around the site is used to plant maize only. Micrometeorological variables, including temperature of the air, relative humidity, speed of wind, four-component radiation, the profile of the temperature of the soil, and the flux of soil heat were recorded at 0.5 Hz, with means taken every 10 min using a collection of micrometeorological sensors installed above the plant canopy and in the soil. Data reported in the current study were averaged to hourly intervals from the 25th of May to the 15 September 2012 and used as input for modeling. Further details of data acquisition are described in the literature [34].

Simulated $ET_0$ partitioning results (e.g., $T_0$ and $E_0$) are difficult to be observed and determined in practice. Therefore, it is difficult to verify. However, associated actual evapotranspiration partitioning results (e.g., actual transpiration, T) can be observed in practice. In order to verify the model partitioning performance in the study site, we obtained the previous study of $ET_a$ partitioning results estimated by the independent uWUE method [35].

3. Results

3.1. R-SPAC Model Performance in Simulating $ET_0$

The present study compared simulations of $ET_0$ between the FAO-PM and R-SPAC models (Figure 2). As shown in Table 1, the R-SPAC model simulations of $ET_0$ were similar to those of the FAO-PM model, as indicated by the index of agreement (I) of 0.99 and
root-mean-square deviation (RMSD) of 0.05 mm h\(^{-1}\). The simulations both of daily and diurnal variations by R-SPAC models were similar to those of estimated by FAO-PM, with an R\(^2\) of 0.98.

![Graph showing similarity of simulations of reference evapotranspiration (ET\(_0\)) by the Penman–Monteith approach by the Food and Agriculture Organization (FAO-PM) and the reference soil–plant–atmosphere continuum (R-SPAC) model.]

\[
Y = 0.85 \times X + 0.04 \\
R^2 = 0.96 \\
P < 0.01
\]

Table 1. Statistical summary of the performance of the reference soil–plant–atmosphere continuum (R-SPAC) model in simulating reference evapotranspiration (ET\(_0\)) and associated SPAC in simulating actual evapotranspiration (ET\(_a\)) and its partitioning for actual transpiration (T).

| Variables                  | Dataset       | Unit   | \(^2\) RMSD | I index | R\(^2\) | n  |
|----------------------------|---------------|--------|-------------|---------|---------|----|
| Reference Evapotranspiration, ET\(_0\) | All dataset | mm h\(^{-1}\) | 0.05 | 0.98     | 0.96 | 2813 |
| Daily time                 | mm h\(^{-1}\) | 0.05   | 0.99        | 0.96 | 1046   |
| Actual Evapotranspiration, ET\(_a\) | All dataset | W m\(^{-2}\) | 47.90 | 0.96     | 0.87 | 1464 |
| Actual Transpiration, T    | All dataset  | mm h\(^{-1}\) | 0.11 | 0.82     | 0.80 | 335  |

\(^1\) 8:00am–16:00pm. \(^2\) root mean square difference. \(^3\) Hourly mean T dataset was obtained from Zhou et al., 2018 [35].

In order to further demonstrate our modeling performance and its validity, we evaluate the modeling performance under the actual land surface conditions. For actual evapotranspiration (ET\(_a\)) and its partitioning (e.g., actual transpiration, T), as summarized in Table 1, the simulations of ET\(_a\) (T) have good agreement to measured ET\(_a\) (T) by eddy covariance (uWUE approach), as indicated by the index of agreement (I) of 0.96 (0.82) and RMSD of 47.90 W m\(^{-2}\) (0.11 mm h\(^{-1}\)). The simulations of seasonal variations by the actual SPAC model were in agreement with those measured by EC and estimated by uWUE with an R\(^2\) of 0.87 (0.80).
3.2. Seasonal Variations in \( \text{ET}_0 \)

Figure 3 shows the diurnal and seasonal variations in simulated \( \text{ET}_0 \) during the growing season by both the FAO-PM and R-SPAC models. The estimated means and seasonal variations in \( \text{ET}_0 \) by the FAO-PM and R-SPAC models were 0.18 mm h\(^{-1}\) ± 0.29 mm h\(^{-1}\) and 0.19 mm h\(^{-1}\) ± 0.25 mm h\(^{-1}\), respectively. Simulations of both models showed well-constructed diurnal and seasonal variations and no significant systematic bias \((P < 0.01)\) during the growing season.

![Figure 3](image-url)

**Figure 3.** Seasonal variations in simulated reference evapotranspiration \((\text{ET}_0)\) by two models during the growing season. The gray lines represent simulations by the reference soil-plant-atmosphere continuum (R-SPAC) model, whereas black dots represent simulations by the Penman–Monteith model by the Food and Agriculture Organization (FAO-PM).

3.3. Partitioning of \( \text{ET}_0 \)

Figure 4 illustrates diurnal and seasonal variations in simulated \( \text{ET}_0 \) components over the growing season by the R-SPAC model. The estimated mean and seasonal variation in \( \text{ET}_0 \) for soil evaporation \((\text{E}_0)\) and plant transpiration \((\text{T}_0)\) were 0.12 mm h\(^{-1}\) ± 0.16 mm h\(^{-1}\) and 0.09 mm h\(^{-1}\) ± 0.09 mm h\(^{-1}\), respectively. Dominant components of \( \text{ET}_0 \) at the study site are \( \text{T}_0 \) over the growing season, with the mean contribution and seasonal deviation of transpiration fraction \((\text{T}_0/\text{ET}_0)\) being 0.63 ± 0.28.

3.4. Results of Sensitivity Analysis

Table 2 shows the sensitivity of input variables to \( \text{ET}_0 \) and its components. Among many climate factors, downward short-wave radiation \((\text{S}_d)\) was the most sensitive to \( \text{ET}_0 \), followed by downward long-wave radiation \((\text{L}_d)\) and air temperature \((\text{T}_a)\). Changes in \( \text{S}_d \), \( \text{L}_d \) and \( \text{T}_a \) of 5\% resulted in changes in \( \text{ET}_0 \) of 4.4\%, 3.3\%, and 2.2\% respectively. For \( \text{T}_0 \), \( \text{S}_d \) was the most sensitive factors with sensitivity coefficient of 0.98; \( \text{L}_d \) and \( \text{T}_a \) followed with sensitivity coefficients 0.80 and 0.56. For \( \text{E}_0 \), \( \text{S}_d \) was the most sensitive factor followed by \( \text{L}_d \) and relative humidity \((h_a)\). Changes in \( \text{S}_d \), \( \text{L}_d \), and \( h_a \) of 5\% resulted in changes in \( \text{E}_0 \) of 3.2\%, 2.4\%, and −2.1\%, respectively.
Figure 4. Seasonal variations in reference evapotranspiration (ET0) components as simulated by the reference soil–plant–atmosphere continuum (R-SPAC) model over the growing season. The gray line represents shows transpiration, whereas the black line represents reference evaporation.

Table 2. Mean and standard deviation in sensitivity coefficient (Si) of reference evapotranspiration (ET0) and its components (T0 and E0) to the measured variables.

| Variables | T0 Mean (s.d.) | E0 Mean (s.d.) | ET0 Mean (s.d.) |
|-----------|----------------|----------------|-----------------|
| Sd        | 0.98 (0.30)    | 0.64 (0.23)    | 0.89 (0.29)     |
| Ld        | 0.80 (0.47)    | 0.49 (0.31)    | 0.67 (0.39)     |
| u         | 0.22 (0.14)    | 0.27 (0.11)    | 0.25 (0.12)     |
| Ta        | 0.56 (0.13)    | 0.28 (0.25)    | 0.44 (0.13)     |
| ha        | −0.12 (0.20)   | −0.42 (0.35)   | −0.23 (0.25)    |
| P         | 0.08 (0.11)    | 0.00 (0.10)    | 0.05 (0.10)     |
| Tss       | 0.05 (0.06)    | 0.38 (0.24)    | 0.18 (0.15)     |

s.d., standard deviation; Sd, downward short-wave radiation; Ld, downward long-wave radiation; u, wind speed; Ta, air temperature; ha, relative humidity; P, air pressure; Tss, soil surface temperature at depth Zss.

4. Discussion
4.1. Modeling Advantages and Limitations

The updated R-SPAC model proposed in the present study showed a good performance in simulating ET0 when compared against the FAO-PM approach. These results of the present study confirmed the validity and usefulness of the use of the R-SPAC model for estimating ET0 in a reference agricultural catchment. Although previous studies have shown similar performances to that of the current study through the use of other approaches [8,9,19,36,37], the use of the R-SPAC model offers various advantages. Firstly, the approach proposed in the present study allows the consideration and parameterization of plant factors that affect ET, including crop type, continuous growth processes characterized by leaf area index and canopy height development, and crop canopy structure that
affects the plant canopy and geometry. Secondly, the R-SPAC model provides a rigorous consideration of the balance between energy and radiation in both the canopy of reference plants and at the surface of the ground, as well as their interactions, thereby facilitating the estimation of all the components of the energy balance. These estimations can then be validated against those of the standard FAO-PM model. Thirdly, the R-SPAC uses the NR scheme to estimate $T_L$ and $T_G$ in a simple, stable, and rapid manner without the need for measurements of directional radiometric temperature; meanwhile, the estimations of $T_L$ and $T_G$ are more sensitive to the partitioning of ET compared to ET itself, and they can be useful for the validation of models. Based on the calculated $T_L$ and $T_G$, the partitioning of ET becomes a matter of course. However, there remains scope for further modification and improvement of the R-SPAC model. The present study used arbitrarily constant values for some parameters (e.g., LAI, $Z_v$, and albedo of $1 \text{ m}^2 \text{ m}^{-2}$, $1.2 \text{ m}$, and $0.23$, respectively) throughout the periods investigated, and these assumptions may account for errors in estimating crop-specific ET$_C$. The present study focus on ET$_0$ without considering various management practices (e.g., Plastic mulches) and not consider dynamics in the non-growing season [20,25].

4.2. Controls of ET$_0$

Increasing attention to global warming has produced many reports on decreasing trends in reference evapotranspiration and the associated climatic controls. These trends are likely the result of decreases in sunshine duration over China [38] that may be related to increases in air pollution and atmospheric aerosols [39], increases in cloud cover [40], and decreased wind speed [41]. A study in the Jinhe River Basin showed that reductions in ET$_0$ were principally the result of significant decreases in wind speed as well as sunshine hours [42]. The present study identified perhaps net radiation (Figure 5a) or short-wave radiation (Figure 5b) as the main drivers of seasonal variations in ET$_0$ through changing available energy ($R_n$-G). Although some previous reports [41] have emphasized the importance of wind speed in driving variations in ET$_0$, the results of the present study suggest that variation in solar radiation is the dominant driver of ET$_0$, at least at the study site of the present study.

![Figure 5](image)

**Figure 5.** Relationship between downward solar radiation and reference evapotranspiration (ET$_0$) simulated by (a) the Penman–Monteith method by the Food and Agriculture Organization (FAO-PM) and (b) the reference soil–plant–atmosphere continuum (R-SPAC) model.

4.3. Implications and Prospective Research Directions

Evapotranspiration is a comprehensive result of the interaction of climate, vegetation, and soil, which can be esitimated by ET$_0$, ET$_P$, and ET$_a$, respectively [1,27,43]. A reference evapotranspiration (ET$_0$) and its components (reference transpiration and reference soil
evaporation) are calculated assuming that the reference land surface is wet and well-managed [1]. A potential evapotranspiration (ET$_p$) and its components (potential transpiration and potential soil evaporation) are calculated assuming that when the land surface is wet, total evapotranspiration flux consumes the whole available energy [27]. The ET$_a$ and its components are calculated by actual land surface conditions [28,44]. The successful application of the R-SPAC model to the scheduling of irrigation (e.g., dynamics of the crop coefficient) requires determining the relationship between reference crop ET and ET of the target crop through the use of crop growth information (e.g., dynamics of leaf area index (LAI) and $Z_V$, stomatal behavior). The model shows promise for the calculation of the continuous crop coefficients (C$_p$ = ET$_0$/ET$_p$) as well as ecosystem/plant water stress coefficients (K$_s$ = ET$_a$/ET$_p$) throughout the growing season under various land surface scenarios; for example, reference land surface for ET$_0$, actual land surface with adequate soil moisture for ET$_p$, and actual land surface with actual soil moisture for ET$_a$ [25,28]. Moreover, the model can be further extended to estimated ET$_0$, ET$_p$, and ET$_a$ in non-agricultural ecosystems, such as forests and other perennial vegetation [27,43]. It is promising to quantify the seasonal dynamics of C$_p$ and K$_s$ in different ecosystems, which is of great significance for predicting the ecohydrological response to climate change and accurately quantifying the water use on basins to global scale.

5. Conclusions
The present study updated and applied the R-SPAC model for the simulation of diurnal and seasonal variations in ET$_0$. Simulations of ET$_0$ by the R-SPAC model were consistent with those of the FAO-PM model, thereby confirming the accuracy of the R-SPAC model. The present study used sensitivity analysis to explore uncertainties/errors in ET$_0$ and components in input variables. The results of the present study showed that the R-SPAC model is a useful tool to partition ET$_0$. The present study showed that the principal factor controlling diurnal and seasonal variations in ET$_0$ at the investigated site is solar radiation. It is promising to estimate ET$_0$, ET$_p$, and ET$_a$ under various land surface scenarios and quantify the seasonal dynamics of C$_p$ and K$_s$ in crop and other different ecosystems.

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