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# Modelling Evaporation and Evapotranspiration under Temperature Change in Malaysia

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## ABSTRAK

Perubahan suhu berkesan terus keatas hidrologi melalui hubungannya dengan sejatpemeluhan. Impak potensi pertukaran iklim terhadap sejatpemeluhan ditaksirkan, dengan menggunakan satu pendekatan model yang berasaskan beberapa ukuran fizikal cuaca. Kaedah- kaedah untuk menganggarkan sejatan permukaan bebas, $E_p$, dan sejatpemeluhan potensi, $ET_p$, tanpa menggunakan parameter penentukuran model, untuk masa bersiri bulanan adalah dikemukakan. Keputusan model dikirakan, dengan menggunakan data meteorologi bersejarah purata (1980-97) dan dibandingkan dengan data sejatan panci sejatan kelas A USBR (1971-97) dari Skim Pengairan Muda, Malaysia. Penaksiran harian purata $E_p$ bulanan jangkamasa panjang untuk bulan bulanan dibandingkan dengan sejatan panci terukur. Keputusan simulasi menunjukkan kejituan melebihi 95% dengan data cerapan sejatan panci, dan oleh yang demikian, akan diguna untuk penaksiran $ET_p$. Kesemua persamaan model yang mengandungi sebutan suhu disetkan bersandar kepada suhu. Sekaitan diantara lembapan nisbi min dan suhu juga dibuat demi untuk menyiasat kepekaan $ET_p$. $ET_p$ bersiri masa terkesan dengan perubahan suhu bulanan daripada 21°C sehingga 41°C, bertokokan 0.2°C demi untuk menyiasat kepekaan siri itu. Keputusan daripada gangguan menunjuk bahawa suhu memberi kesan bererti terhadap $ET_p$ untuk setiap bulan.

## ABSTRACT

Temperature change has a direct effect on hydrology through its link with evapotranspiration. The potential impact of temperature change on the evapotranspiration is assessed; using a modelling approach based on a few physical weather measurements. Methods to estimate free-surface evaporation $E_p$ and potential evapotranspiration $ET_p$, without any model calibration parameters, for monthly time series are presented. The model results are calculated by using observed average historic (1980-97) meteorological data and compared with USBR Class-A black pan evaporation data (1971-97) from the Muda Agricultural Development Authority, Malaysia. The long-term monthly averaged daily estimates of $E_p$ for different months were compared with measured pan evaporation. Results of this simulation showed an accuracy of more than 95% with the observed pan evaporation data and thus, would be used for $ET_p$ estimation. All the model equations containing temperature terms were set dependent of temperature. The correlation between mean monthly relative humidity and temperature was also made to investigate the sensitivity of $ET_p$. The $ET_p$ time series is perturbed by varying monthly temperature from 21°C to 41°C, with 0.2°C increment to investigate the sensitivity of that series. Results from the perturbations showed that the temperature has significant effects on $ET_p$ for each month.

**Keywords: temperature change, evaporation, evapotranspiration, simulation, perturbation**

## INTRODUCTION

In recent years, increased awareness of environmental issues has led to the idea of sustainability, in which a watershed is controlled to maintain a balance between the availability and the use of its resources. To obtain water sustainability, the planners must envisage how climate interacts with various aspects of the water cycle. This means understanding the link between climate and evapotranspiration. Climatic conditions, which determine both the scale and the temporal distribution of watershed hydrology, may attenuate or accentuate evapotranspiration. In the Muda area, Malaysia, it is found from the observed data (1971-1997) that the mean annual actual evaporation can account for 67% of the mean annual precipitation. Thus, a good estimate of evapotranspiration is required if water sustainability is to be achieved. Measurements of evapotranspiration are rarely available and are unlikely to be sufficient to describe the influence on the evapotranspiration regime. In the absence of measurements, an alternative approach is to use mathematical models to predict the variations in evapotranspiration, using meteorological data to describe variations in the temperature.

The present study employs the Penman-Monteith potential evapotranspiration model (Monteith 1965), to estimate $ET_p$ and the Penman equation is used to estimate the free-surface or potential evaporation $E_p$. The aims of this paper are: (i) to compare model $E_p$ with the observed pan evaporation, (ii) to use the model $E_p$ in $ET_p$ estimation, and (iii) to assess the potential impact of temperature variations on the predicted $ET_p$.

## POTENTIAL EVAPORATION AND EVAPOTRANSPIRATION MODELING

Evapotranspiration involves a highly complex set of processes, which are influenced by many factors dependent on the local conditions. These conditions range from precipitation and meteorology to soil moisture, plant water requirements and the physical nature of the land cover (Dunn and Mackay 1995). The primary reason for differentiating between the free-surface evaporation $E_p$ and potential evapotranspiration $ET_p$ is that the diffusion of water vapor into the atmosphere follows very different pathways in vegetation (transpiration) than it does from free-water-surface water. Gangopadhyaya *et al.* (1966) defined potential evapotranspiration ET as "the maximum quantity of water capable of being lost, as water vapor, in a given climate, by a continuous, extensive stretch of vegetation covering the whole ground when the soil is kept saturated." Gangopadhyaya's definition of ET therefore recognizes the combined process of transpiration by vegetation and evaporation from saturated bare soil. Estimating $ET_p$ is more difficult than estimating $E_p$ because several vegetation-species-specific model parameters are required. Many simple models to predict the potential evaporation rate exist, such as the Penman formula (Penman 1948) and the Thornthwaite formula (Thornthwaite 1948). These models do not give any indication of how the potential rate may be converted to give an actual evapotranspiration rate as a function of the vegetation type and the soil moisture conditions. However, the only process based model that is widely used, and that accounts for the influence of vegetation on the evapotranspiration regime, is the Penman-Monteith energy formula (Monteith 1965). There are several reasons why the Penman-Monteith energy-balance equation is chosen to estimate the potential evapotranspiration in the present study (Fennessy and Kirshen 1994). Firstly, the Penman-Monteith equation "big leaf" model is presently used by a number of general circulation models (GCMs) to estimate the flux of energy and moisture between the atmosphere and the land surface/ water surface boundaries, as described by Milly (1992). Secondly, the model is composed of a number of the GCM prognostic variables, thus lending itself to easy perturbation by climate-change scenarios. Lastly, the model is derived from the energy-conservation equations, and therefore it is generally considered to be universally applicable.

The Penman-Monteith potential evapotranspiration model (Monteith 1965) is

$$ET_p = \frac{\Delta(R_n - G) + \dfrac{\rho_a C_p\left[e^\circ(z) - e_d(z)\right]}{r}}{\lambda\left(\Delta + \gamma\left[1 + \dfrac{r_s}{r_a}\right]\right)} \tag{1}$$

where, $ET_p$ is the potential evapotranspiration (mm/day); $\lambda$ is the latent heat of vaporization of water (MJ $kg^{-1}$); $\Delta$ is the gradient of the saturation-vapour-pressure-temperature function (kPa $^0C^{-1}$); $R_n$ is the net radiation (MJ $m^{-2}$ $day^{-1}$); G is the soil heat flux (MJ $m^{-2}$ $day^{-1}$); $\rho_a$ is the air density (kg $m^{-3}$); $C_p$ is the specific heat of the air at constant pressure = 1.013 kJ $kg^{-1}$ $K^{-1}$; $e^o(z)$ is the saturated vapour pressure of the air (kPa), a function of air temperature measured at height z; $e_d(z)$ is the mean actual vapor pressure of the air measured at height z (kPa); $r_a$ is the aerodynamic resistance to water-vapor diffusion into the atmospheric boundary layer (s $m^{-1}$); $\gamma$ is the psychrometric constant (kPa $^0C^{-1}$); and $r_s$ is the vegetation canopy resistance to water-vapour transfer (s $m^{-1}$).

One of the limitations of the Penman-Monteith equation is its data requirements. At a minimum, the model requires air temperature, wind speed, solar radiation, and the saturation-vapour-pressure deficit. Methods employed to determine the solar radiation and vapour pressure deficit are described below.

In Eq. (1), the net radiation $R_n$ is described by

$$R_n = (1 - a)R_s - R_{nl} \tag{2}$$

where $R_s$ (MJ $m^{-2}$ $day^{-1}$) is the short-wave solar radiation; $\alpha$ is the surface reflectivity or albedo, whose recommended values are 0.08 for open water surfaces and 0.23 for most of the crops; and $R_{nl}$ (MJ $m^{-2}$ $day^{-1}$) net longwave outgoing radiation.

The quantity of $R_s$ can be computed as

$$R_s\left(0.25 + 0.50\frac{n}{N}\right)R_a \tag{2a}$$

where $R_a$ is the extraterrestrial solar radiation (MJ $m^{-2}$ $day^{-1}$), n is the actual number of hours of bright sunshine (h/day); N is the possible maximum number of sunshine hours (h/day).

Penman (1948) suggested an expression for $R_{nl}$ as

$$R_{nl} = \sigma T_a^4\left[0.56 - 0.092(e_d)^{0.5}\right]\left(0.1 + 0.9\frac{n}{N}\right) \tag{2b}$$

where $\alpha$ is the Stefan-Boltzmann constant = 4.903 x $10^{-9}$ MJ $m^{-2}$ $K^{-4}$ $day^{-1}$; $T_a$ is the mean air temperature in $^0$C; and $e_d$ is the mean actual vapour pressure of the atmosphere at dew point temperature $= \frac{RH_{mean}}{100} e^0$ (kPa) ; in which $RH_{mean}$ is the mean relative humidity (%) and $e^0$ is the saturation vapour pressure of the evaporating surface at mean air temperature.

Substituting $R_s$ and $R_{nl}$ from Eqs. (2a), and (2b) into Eq. (2) respectively,

$$R_n = (1 - a)\left(0.25 + 0.50\frac{n}{N}\right)R_a - \sigma T_a^4\left[0.56 - 0.092(e_d)^{0.5}\right]\left(0.1 + 0.9\frac{n}{N}\right) \tag{3}$$

The soil heat flux G (MJ $m^{-2}$ $day^{-1}$) can be computed by using the following equation

$$G = c_s d_s \frac{T_2 - T_1}{\Delta t} \tag{4}$$

where $T_2$ is the temperature at the end of the period ($^0C$); $T_1$ is the temperature at the beginning of the period ($^0C$); $\Delta t$ is the length of period (days); $c_s$ is the soil heat capacity (2.1 MJ $m^{-3}\,{}^0C^{-1}$) for average moist soil; and $d_s$ is the estimated effective soil depth (m).

For daily temperature fluctuations (effective soil depth typically 0.18 m) Eq. (4) becomes

$$G = 0.38(T_{day2} - T_{day1}) \tag{5}$$

The right-hand term of the numerator of Eq. (1), incorporates the saturation-vapour-pressure deficit (the term enclosed by brackets), which is estimated by

$$e^o(z) - e_d(z) = e^o(z, T_a)\left(1 - \frac{RH_{mean}}{100}\right) \tag{6}$$

In Eq. (6), the saturated vapour pressure is estimated by the methods described by Tetens (1930) and Murray (1967), and is described by

$$e^o(T_a) = \exp\left(\frac{16.78T_a - 116.9}{T_a + 237.3}\right) \tag{7}$$

In Eq. (1), the slope of the saturation vapour pressure-temperature curve $\Delta$ is estimated by the methods described by Tetens (1930) and Murray (1967), and is described by

$$\Delta = \frac{4098e^o}{(T_a + 237.3)^2} \tag{8}$$

The latent heat of vaporization of water $\lambda$ is estimated using the method described by Harrison (1963), shown here as

$$\lambda = 2501 - 2.361 \times 10^{-3} T_a \tag{9}$$

The phychrometric constant $\gamma$ is estimated by

$$\gamma = \frac{C_p P_a}{0.662\lambda} \tag{10}$$

In Eq. (10), the specific heat of moist air ($C_p$) is assumed to equal 1.013 $kJ.kg^{-1}.K^{-1}$, as reported by Brutsaert (1982). The atmospheric pressure $P_a$(kPa) can be computed as

$$P_a = 101.3 - 0.01152z + 0.544 \times 10^{-6} z^2 \tag{11}$$

where z is the elevation above mean sea level (m).

The density of (moist) air $\rho_a$(kg m$^{-3}$) can be calculated from the ideal gas laws, but it is adequately estimated from

$$\rho_a = 3.486 \frac{P_a}{275 + T_a} \tag{12}$$

The rate of water vapor transfer away from the ground by turbulent diffusion is controlled by aerodynamic resistance $r_a$ (s m$^{-1}$) and can be estimated from

$$r_a = \frac{4.72\left[\ln\left(\frac{z}{z_0}\right)\right]^2}{1 + 0.536U_2} \tag{13}$$

where z is the height at which meteorological variables are measured (m); $z_0$ is the aerodynamic roughness of the surface = 0.00137m; and $U_2$ is the average wind speed at 2m height (m/s). $U_2$ (km/h) can be computed from observations at any height as $U_2 = U_h\left(\frac{2.0}{h}\right)^{0.143}$ where $U_h$ is the observed wind speed (km/h) at a height of h meters.

The stomata resistance of the whole canopy, referred to as the surface resistance $r_s$, is less when more leaves are present since there are then more stomata through which transpired water vapor can diffuse. In vapour transport, the measure of potential is the vapor pressure and the vapour flux rate E. Thus the vapour flux rate can be approximately estimated for leaf stomata as

$$E = \frac{k_s\left[e^0(z) - e(z)\right]}{r_s} \tag{14}$$

where $k_s$ is a constant to account for units. One approximation for $r_s$ is

$$r_s = \frac{200}{L} \tag{15}$$

If $h_c$ is the mean height of the crop, then the leaf area index L can be estimated by

$$L=24h_c \quad \text{(clipped grass with } 0.05 < h_c < 0.15 \text{ m)}$$
$$L=5.5 + 1.5\ln(h_c) \quad \text{(alfalfa with } 0.10 < h_c < 0.50 \text{ m)} \tag{16}$$

The surface resistance of the reference crop of clipped grass $r_s^{rc}$ of 0.12m high is estimated as

$$r_s^{rc} = 69 \text{ s m}^{-1} \tag{17}$$

Since potential evaporation occurs from an extensive free water surface, it follows that the canopy resistance $r_s = 0$ is the appropriate value of surface resistance for estimating potential evaporation from Eq. (1).

## DATA AND CALCULATIONS OF $E_p$ AND $ET_p$

Long-term monthly averaged daily values of the estimated free-surface evaporation determined in the present study are compared with the USBR class A black pan evaporation measurements (1971-97) by Muda Agricultural Development Authority (MADA). The values quoted here are the average of 30 stations uniformly distributed in Muda area. Similarly, monthly averaged daily values of temperature, wind speed, possible sunshine and relative humidity meteorological data (1980-97), which are all used as input variables to the $E_p$ model, are taken from station 27 (Kepala Batas: Lat. 06°12'N, and Long.100°24'E) of the same Authority. The extra-terrestrial radiation $R_a$ (mm/day) is taken from the literature (Michael 1978) and then multiplied by the latent heat of vaporization of water $\lambda$ (MJ kg$^{-1}$) to convert to $R_a$ (MJ m$^{-2}$ day$^{-1}$) for fulfilling the model requirements. The step-by-step procedures of calculating $E_p$ and $ET_p$ are given in Table 1.

## RESULTS AND DISCUSSION

*Fig. 1* shows that the long-term monthly averaged daily estimates of $E_p$ for different months simulate more than 95% with the observed pan evaporation. The overall matching, considering the total time series, with the pan evaporation is 99%. The *relative error* = (Pan $E_p$ – Model $E_p$)/Pan $E_p$ between the observed and model results is shown in *Fig. 2*.

The surface resistance $r_s$ of the crop, assuming seasonal average crop height of 0.2m, is incorporated in $ET_p$ modeling instead of using crop coefficient $K_c$. Incorporating actual crop height might yield more accurate results than calculated, as the crop height is variable from time to time. In the absence of relevant data, the typical effective soil depth of 0.18m (Wyjk van and de Vries 1963) is considered for daily temperature fluctuations in calculating the soil heat flux G. Since measurements of evapotranspiration are not available at MADA, an alternative approach is to use mathematical models to predict the

TABLE 1
Estimating potential evaporation and evapotranspiration by Penman-Monteith Equation

| Parameter | Month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec |
| *Avg. Temp., $T_a$ (°C) | 26.99 | 27.66 | 27.96 | 28.12 | 27.84 | 27.63 | 27.06 | 26.90 | 26.71 | 26.60 | 26.58 | 26.47 |
| *Avg. $RH_{mean}$ (%) | 72.90 | 73.00 | 76.60 | 81.50 | 85.20 | 85.60 | 86.30 | 86.30 | 86.40 | 87.00 | 85.00 | 79.70 |
| *Avg. $U_2$ (m/s) at 2m altitude | 1.39 | 1.28 | 1.04 | 0.90 | 0.82 | 0.74 | 0.80 | 0.83 | 0.84 | 0.78 | 0.82 | 1.16 |
| $e_d(z)$ (kPa) | 2.60 | 2.71 | 2.89 | 3.10 | 3.19 | 3.17 | 3.09 | 3.06 | 3.03 | 3.03 | 2.96 | 2.76 |
| $R_a$ ($MJ.m^{-2}.day^{-1}$) | 33.81 | 35.98 | 37.47 | 37.54 | 36.82 | 35.88 | 36.36 | 37.10 | 37.30 | 36.52 | 34.55 | 33.31 |
| $e^\circ(z)$ (kPa) | 3.57 | 3.71 | 3.77 | 3.81 | 3.75 | 3.70 | 3.58 | 3.55 | 3.51 | 3.48 | 3.48 | 3.46 |
| $e^\circ(z)-e_d(z)$ (kPa) | 0.97 | 1.00 | 0.88 | 0.70 | 0.55 | 0.53 | 0.49 | 0.49 | 0.48 | 0.45 | 0.52 | 0.70 |
| $\lambda$ ($MJ\ kg^{-1}$) | 2.44 | 2.44 | 2.43 | 2.43 | 2.44 | 2.44 | 2.44 | 2.44 | 2.44 | 2.44 | 2.44 | 2.44 |
| *Sunshine, n (h/day) | 8.70 | 9.00 | 8.50 | 8.70 | 7.70 | 7.10 | 6.60 | 6.70 | 5.70 | 5.70 | 6.10 | 7.00 |
| n/N (cloudiness fraction) (N=9h) | 0.97 | 1.00 | 0.94 | 0.97 | 0.86 | 0.79 | 0.73 | 0.74 | 0.63 | 0.63 | 0.68 | 0.78 |
| $R_n$ ($MJ.m^{-2}.day^{-1}$) | 19.09 | 20.78 | 20.84 | 21.20 | 19.22 | 17.80 | 17.27 | 17.77 | 16.28 | 15.94 | 15.67 | 16.39 |
| $P_a$ (kPa) | 101.16 | 101.16 | 101.16 | 101.16 | 101.16 | 101.16 | 101.16 | 101.16 | 101.16 | 101.16 | 101.16 | 101.16 |
| G ($MJ.m^{-2}.day^{-1}$) | 0.26 | 0.11 | 0.06 | -0.11 | -0.08 | -0.22 | -0.06 | -0.07 | -0.04 | -0.01 | -0.04 | 0.20 |
| $\gamma$ ($kPa^\circ C^{-1}$) | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 |
| $\rho_a$ ($kg\ m^{-3}$) | 1.17 | 1.17 | 1.16 | 1.16 | 1.16 | 1.17 | 1.17 | 1.17 | 1.17 | 1.17 | 1.17 | 1.17 |
| $\Delta$ ($kPa^\circ C^{-1}$) | 0.21 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.21 | 0.21 | 0.21 | 0.21 | 0.20 | 0.20 |
| $r_a$ ($s.m^{-1}$) | 143.50 | 148.59 | 160.81 | 169.16 | 173.84 | 179.52 | 175.05 | 173.33 | 172.48 | 176.81 | 173.84 | 154.73 |
| Model $E_p$ (mm/day) | 5.94 | 6.57 | 6.63 | 6.81 | 6.14 | 5.72 | 5.46 | 5.62 | 5.12 | 5.00 | 4.92 | 5.07 |
| *Pan $E_p$ (mm/day) | 6.12 | 7.07 | 6.79 | 6.56 | 5.65 | 5.46 | 5.24 | 5.49 | 5.46 | 5.10 | 5.25 | 5.23 |
| $r_s$ ($s.m^{-1}$) at average $h_c$ = 0.2m | 64.81 | 64.81 | 64.81 | 64.81 | 64.81 | 64.81 | 64.81 | 64.81 | 64.81 | 64.81 | 64.81 | 64.81 |
| $ET_p$ (mm/day) | 5.37 | 5.98 | 6.08 | 6.27 | 5.67 | 5.29 | 5.03 | 5.16 | 4.71 | 4.60 | 4.52 | 4.61 |

• Observed Data (Source: Muda Agricultural Development Authority, Alor Setar, Kedah, Malaysia)

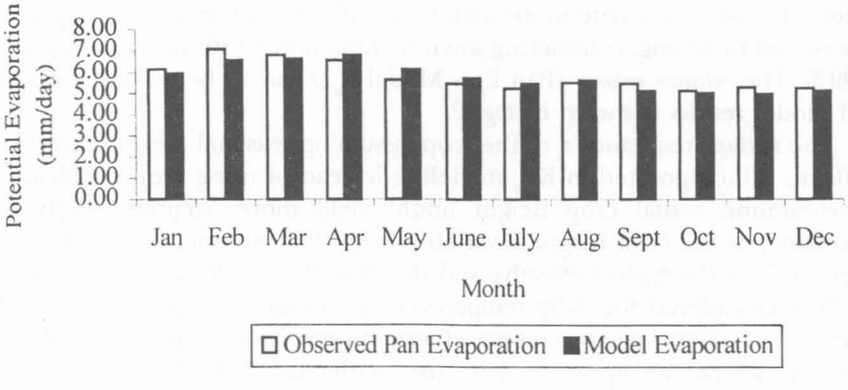


*Fig 1. Simulating calculated evaporation with observed pan evaporation*

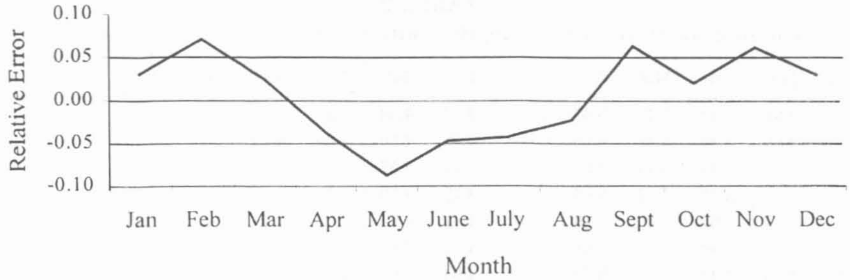


*Fig 2. Relative error between observed and calculated evaporation rates*

variations in evapotranspiration, with meteorological data describing variations in the climate.

To study the theoretical variations in the evapotranspiration predictions across the Muda area, as influenced by climate, $ET_p$ model parameters are set dependent of temperature. The correlation between mean monthly temperature and relative humidity is also performed using observed values and is shown in *Fig. 3.*

The $ET_p$ time series is perturbed by varying monthly temperature from 21°C to 41°C with +0.2°C increment to investigate the sensitivity of $ET_p$. The variations of $ET_p$ for each month with temperature change are given in Table 2. The average variation, which corresponds to the same temperature perturbation, is plotted and shown in *Fig. 4.* The results from the perturbations show that the temperature has significant effects on $ET_p$ for each month.

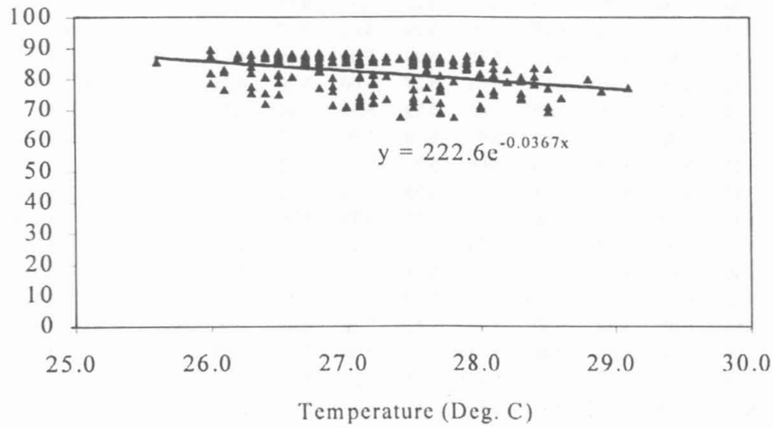


*Fig 3. Correlation between mean monthly temperature and relative humidity*

TABLE 2
Variation of model $ET_p$ (mm/day) with temperature for each month

| $T_a$(°C) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 21.0 | 4.83 | 5.29 | 5.40 | 5.57 | 5.06 | 4.74 | 4.54 | 4.67 | 4.27 | 4.18 | 4.11 | 4.19 | 4.74 |
| 21.2 | 4.85 | 5.31 | 5.42 | 5.59 | 5.08 | 4.75 | 4.56 | 4.69 | 4.28 | 4.20 | 4.13 | 4.20 | 4.75 |
| 21.4 | 4.87 | 5.33 | 5.44 | 5.61 | 5.10 | 4.77 | 4.57 | 4.71 | 4.30 | 4.21 | 4.14 | 4.22 | 4.77 |
| 21.6 | 4.89 | 5.35 | 5.47 | 5.63 | 5.11 | 4.79 | 4.59 | 4.72 | 4.32 | 4.23 | 4.16 | 4.24 | 4.79 |
| 21.8 | 4.91 | 5.37 | 5.49 | 5.65 | 5.13 | 4.81 | 4.61 | 4.74 | 4.33 | 4.24 | 4.17 | 4.25 | 4.81 |
| 22.0 | 4.93 | 5.39 | 5.51 | 5.68 | 5.15 | 4.82 | 4.63 | 4.76 | 4.35 | 4.26 | 4.19 | 4.27 | 4.83 |
| 22.2 | 4.95 | 5.41 | 5.53 | 5.70 | 5.17 | 4.84 | 4.64 | 4.78 | 4.37 | 4.27 | 4.21 | 4.28 | 4.85 |
| 22.4 | 4.96 | 5.43 | 5.55 | 5.72 | 5.19 | 4.86 | 4.66 | 4.79 | 4.38 | 4.29 | 4.22 | 4.30 | 4.86 |
| 22.6 | 4.98 | 5.45 | 5.57 | 5.74 | 5.21 | 4.88 | 4.68 | 4.81 | 4.40 | 4.31 | 4.24 | 4.32 | 4.88 |
| 22.8 | 5.00 | 5.47 | 5.59 | 5.76 | 5.23 | 4.90 | 4.69 | 4.83 | 4.41 | 4.32 | 4.25 | 4.33 | 4.90 |
| 23.0 | 5.02 | 5.49 | 5.61 | 5.78 | 5.25 | 4.91 | 4.71 | 4.85 | 4.43 | 4.34 | 4.27 | 4.35 | 4.92 |
| 23.2 | 5.04 | 5.51 | 5.63 | 5.80 | 5.27 | 4.93 | 4.73 | 4.86 | 4.44 | 4.35 | 4.28 | 4.36 | 4.93 |
| 23.4 | 5.06 | 5.53 | 5.65 | 5.82 | 5.28 | 4.95 | 4.74 | 4.88 | 4.46 | 4.37 | 4.30 | 4.38 | 4.95 |
| 23.6 | 5.07 | 5.55 | 5.67 | 5.84 | 5.30 | 4.96 | 4.76 | 4.90 | 4.48 | 4.38 | 4.31 | 4.39 | 4.97 |
| 23.8 | 5.09 | 5.57 | 5.69 | 5.86 | 5.32 | 4.98 | 4.78 | 4.91 | 4.49 | 4.40 | 4.33 | 4.41 | 4.99 |
| 24.0 | 5.11 | 5.59 | 5.71 | 5.88 | 5.34 | 5.00 | 4.79 | 4.93 | 4.51 | 4.41 | 4.34 | 4.43 | 5.00 |
| 24.2 | 5.13 | 5.61 | 5.73 | 5.90 | 5.36 | 5.01 | 4.81 | 4.95 | 4.52 | 4.43 | 4.36 | 4.44 | 5.02 |
| 24.4 | 5.15 | 5.63 | 5.75 | 5.92 | 5.37 | 5.03 | 4.83 | 4.96 | 4.54 | 4.44 | 4.37 | 4.46 | 5.04 |
| 24.6 | 5.16 | 5.65 | 5.77 | 5.94 | 5.39 | 5.05 | 4.84 | 4.98 | 4.55 | 4.46 | 4.38 | 4.47 | 5.05 |
| 24.8 | 5.18 | 5.67 | 5.79 | 5.96 | 5.41 | 5.06 | 4.86 | 5.00 | 4.57 | 4.47 | 4.40 | 4.49 | 5.07 |
| 25.0 | 5.20 | 5.69 | 5.80 | 5.98 | 5.43 | 5.08 | 4.87 | 5.01 | 4.58 | 4.49 | 4.41 | 4.50 | 5.09 |
| 25.2 | 5.22 | 5.71 | 5.82 | 6.00 | 5.45 | 5.10 | 4.89 | 5.03 | 4.60 | 4.50 | 4.43 | 4.52 | 5.10 |
| 25.4 | 5.23 | 5.73 | 5.84 | 6.02 | 5.46 | 5.11 | 4.90 | 5.05 | 4.61 | 4.51 | 4.44 | 4.53 | 5.12 |
| 25.6 | 5.25 | 5.75 | 5.86 | 6.04 | 5.48 | 5.13 | 4.92 | 5.06 | 4.63 | 4.53 | 4.46 | 4.55 | 5.14 |
| 25.8 | 5.27 | 5.76 | 5.88 | 6.06 | 5.50 | 5.15 | 4.94 | 5.08 | 4.64 | 4.54 | 4.47 | 4.56 | 5.15 |
| 26.0 | 5.29 | 5.78 | 5.90 | 6.08 | 5.51 | 5.16 | 4.95 | 5.09 | 4.66 | 4.56 | 4.48 | 4.58 | 5.17 |
| 26.2 | 5.30 | 5.80 | 5.92 | 6.09 | 5.53 | 5.18 | 4.97 | 5.11 | 4.67 | 4.57 | 4.50 | 4.59 | 5.19 |
| 26.4 | 5.32 | 5.82 | 5.94 | 6.11 | 5.55 | 5.19 | 4.98 | 5.13 | 4.68 | 4.59 | 4.51 | 4.60 | 5.20 |
| 26.6 | 5.34 | 5.84 | 5.95 | 6.13 | 5.57 | 5.21 | 5.00 | 5.14 | 4.70 | 4.60 | 4.53 | 4.62 | 5.22 |
| 26.8 | 5.35 | 5.86 | 5.97 | 6.15 | 5.58 | 5.23 | 5.01 | 5.16 | 4.71 | 4.61 | 4.54 | 4.63 | 5.23 |
| 27.0 | 5.37 | 5.87 | 5.99 | 6.17 | 5.60 | 5.24 | 5.03 | 5.17 | 4.73 | 4.63 | 4.55 | 4.65 | 5.25 |
| 27.2 | 5.39 | 5.89 | 6.01 | 6.19 | 5.62 | 5.26 | 5.04 | 5.19 | 4.74 | 4.64 | 4.57 | 4.66 | 5.27 |
| 27.4 | 5.40 | 5.91 | 6.03 | 6.21 | 5.63 | 5.27 | 5.06 | 5.20 | 4.76 | 4.66 | 4.58 | 4.68 | 5.28 |
| 27.6 | 5.42 | 5.93 | 6.05 | 6.22 | 5.65 | 5.29 | 5.07 | 5.22 | 4.77 | 4.67 | 4.59 | 4.69 | 5.30 |
| 27.8 | 5.44 | 5.95 | 6.06 | 6.24 | 5.67 | 5.30 | 5.09 | 5.23 | 4.78 | 4.68 | 4.61 | 4.70 | 5.31 |
| 28.0 | 5.45 | 5.96 | 6.08 | 6.26 | 5.68 | 5.32 | 5.10 | 5.25 | 4.80 | 4.70 | 4.62 | 4.72 | 5.33 |
| 28.2 | 5.47 | 5.98 | 6.10 | 6.28 | 5.70 | 5.33 | 5.12 | 5.26 | 4.81 | 4.71 | 4.63 | 4.73 | 5.34 |
| 28.4 | 5.49 | 6.00 | 6.12 | 6.30 | 5.71 | 5.35 | 5.13 | 5.28 | 4.82 | 4.72 | 4.65 | 4.75 | 5.36 |
| 28.6 | 5.50 | 6.02 | 6.13 | 6.31 | 5.73 | 5.36 | 5.14 | 5.29 | 4.84 | 4.74 | 4.66 | 4.76 | 5.37 |
| 28.8 | 5.52 | 6.03 | 6.15 | 6.33 | 5.75 | 5.38 | 5.16 | 5.31 | 4.85 | 4.75 | 4.67 | 4.77 | 5.39 |
| 29.0 | 5.53 | 6.05 | 6.17 | 6.35 | 5.76 | 5.39 | 5.17 | 5.32 | 4.87 | 4.76 | 4.69 | 4.79 | 5.40 |
| 29.2 | 5.55 | 6.07 | 6.18 | 6.37 | 5.78 | 5.41 | 5.19 | 5.34 | 4.88 | 4.77 | 4.70 | 4.80 | 5.42 |
| 29.4 | 5.56 | 6.08 | 6.20 | 6.38 | 5.79 | 5.42 | 5.20 | 5.35 | 4.89 | 4.79 | 4.71 | 4.81 | 5.43 |
| 29.6 | 5.58 | 6.10 | 6.22 | 6.40 | 5.81 | 5.44 | 5.21 | 5.37 | 4.90 | 4.80 | 4.72 | 4.83 | 5.45 |
| 29.8 | 5.60 | 6.12 | 6.24 | 6.42 | 5.82 | 5.45 | 5.23 | 5.38 | 4.92 | 4.81 | 4.74 | 4.84 | 5.46 |
| 30.0 | 5.61 | 6.13 | 6.25 | 6.44 | 5.84 | 5.46 | 5.24 | 5.39 | 4.93 | 4.83 | 4.75 | 4.85 | 5.48 |
| 30.2 | 5.63 | 6.15 | 6.27 | 6.45 | 5.85 | 5.48 | 5.26 | 5.41 | 4.94 | 4.84 | 4.76 | 4.87 | 5.49 |
| 30.4 | 5.64 | 6.17 | 6.28 | 6.47 | 5.87 | 5.49 | 5.27 | 5.42 | 4.96 | 4.85 | 4.77 | 4.88 | 5.51 |
| 30.6 | 5.66 | 6.18 | 6.30 | 6.49 | 5.88 | 5.51 | 5.28 | 5.44 | 4.97 | 4.86 | 4.79 | 4.89 | 5.52 |
| 30.8 | 5.67 | 6.20 | 6.32 | 6.50 | 5.90 | 5.52 | 5.30 | 5.45 | 4.98 | 4.88 | 4.80 | 4.90 | 5.53 |

Table 2 (Cont'd)

| $T_a$(°C) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 31.0 | 5.69 | 6.22 | 6.33 | 6.52 | 5.91 | 5.53 | 5.31 | 5.46 | 4.99 | 4.89 | 4.81 | 4.92 | 5.55 |
| 31.2 | 5.70 | 6.23 | 6.35 | 6.53 | 5.93 | 5.55 | 5.32 | 5.48 | 5.01 | 4.90 | 4.82 | 4.93 | 5.56 |
| 31.4 | 5.72 | 6.25 | 6.37 | 6.55 | 5.94 | 5.56 | 5.34 | 5.49 | 5.02 | 4.91 | 4.83 | 4.94 | 5.58 |
| 31.6 | 5.73 | 6.26 | 6.38 | 6.57 | 5.96 | 5.58 | 5.35 | 5.51 | 5.03 | 4.92 | 4.85 | 4.95 | 5.59 |
| 31.8 | 5.75 | 6.28 | 6.40 | 6.58 | 5.97 | 5.59 | 5.36 | 5.52 | 5.04 | 4.94 | 4.86 | 4.97 | 5.60 |
| 32.0 | 5.76 | 6.30 | 6.41 | 6.60 | 5.99 | 5.60 | 5.38 | 5.53 | 5.06 | 4.95 | 4.87 | 4.98 | 5.62 |
| 32.2 | 5.77 | 6.31 | 6.43 | 6.62 | 6.00 | 5.62 | 5.39 | 5.55 | 5.07 | 4.96 | 4.88 | 4.99 | 5.63 |
| 32.4 | 5.79 | 6.33 | 6.44 | 6.63 | 6.02 | 5.63 | 5.40 | 5.56 | 5.08 | 4.97 | 4.89 | 5.00 | 5.65 |
| 32.6 | 5.80 | 6.34 | 6.46 | 6.65 | 6.03 | 5.64 | 5.41 | 5.57 | 5.09 | 4.98 | 4.91 | 5.02 | 5.66 |
| 32.8 | 5.82 | 6.36 | 6.47 | 6.66 | 6.04 | 5.66 | 5.43 | 5.58 | 5.10 | 5.00 | 4.92 | 5.03 | 5.67 |
| 33.0 | 5.83 | 6.37 | 6.49 | 6.68 | 6.06 | 5.67 | 5.44 | 5.60 | 5.12 | 5.01 | 4.93 | 5.04 | 5.69 |
| 33.2 | 5.85 | 6.39 | 6.51 | 6.69 | 6.07 | 5.68 | 5.45 | 5.61 | 5.13 | 5.02 | 4.94 | 5.05 | 5.70 |
| 33.4 | 5.86 | 6.40 | 6.52 | 6.71 | 6.09 | 5.69 | 5.46 | 5.62 | 5.14 | 5.03 | 4.95 | 5.06 | 5.71 |
| 33.6 | 5.87 | 6.42 | 6.54 | 6.72 | 6.10 | 5.71 | 5.48 | 5.64 | 5.15 | 5.04 | 4.96 | 5.07 | 5.72 |
| 33.8 | 5.89 | 6.43 | 6.55 | 6.74 | 6.11 | 5.72 | 5.49 | 5.65 | 5.16 | 5.05 | 4.97 | 5.09 | 5.74 |
| 34.0 | 5.90 | 6.45 | 6.56 | 6.75 | 6.13 | 5.73 | 5.50 | 5.66 | 5.17 | 5.06 | 4.98 | 5.10 | 5.75 |
| 34.2 | 5.91 | 6.46 | 6.58 | 6.77 | 6.14 | 5.74 | 5.51 | 5.67 | 5.19 | 5.07 | 5.00 | 5.11 | 5.76 |
| 34.4 | 5.93 | 6.48 | 6.59 | 6.78 | 6.15 | 5.76 | 5.52 | 5.69 | 5.20 | 5.09 | 5.01 | 5.12 | 5.78 |
| 34.6 | 5.94 | 6.49 | 6.61 | 6.80 | 6.17 | 5.77 | 5.54 | 5.70 | 5.21 | 5.10 | 5.02 | 5.13 | 5.79 |
| 34.8 | 5.95 | 6.50 | 6.62 | 6.81 | 6.18 | 5.78 | 5.55 | 5.71 | 5.22 | 5.11 | 5.03 | 5.14 | 5.80 |
| 35.0 | 5.97 | 6.52 | 6.64 | 6.83 | 6.19 | 5.79 | 5.56 | 5.72 | 5.23 | 5.12 | 5.04 | 5.15 | 5.81 |
| 35.2 | 5.98 | 6.53 | 6.65 | 6.84 | 6.21 | 5.81 | 5.57 | 5.73 | 5.24 | 5.13 | 5.05 | 5.17 | 5.83 |
| 35.4 | 5.99 | 6.55 | 6.67 | 6.86 | 6.22 | 5.82 | 5.58 | 5.75 | 5.25 | 5.14 | 5.06 | 5.18 | 5.84 |
| 35.6 | 6.01 | 6.56 | 6.68 | 6.87 | 6.23 | 5.83 | 5.60 | 5.76 | 5.26 | 5.15 | 5.07 | 5.19 | 5.85 |
| 35.8 | 6.02 | 6.58 | 6.69 | 6.88 | 6.24 | 5.84 | 5.61 | 5.77 | 5.27 | 5.16 | 5.08 | 5.20 | 5.87 |
| 36.0 | 6.03 | 6.59 | 6.71 | 6.90 | 6.26 | 5.85 | 5.62 | 5.78 | 5.29 | 5.17 | 5.09 | 5.21 | 5.87 |
| 36.2 | 6.04 | 6.60 | 6.72 | 6.91 | 6.27 | 5.87 | 5.63 | 5.79 | 5.30 | 5.18 | 5.10 | 5.22 | 5.89 |
| 36.4 | 6.06 | 6.62 | 6.73 | 6.93 | 6.28 | 5.88 | 5.64 | 5.80 | 5.31 | 5.19 | 5.11 | 5.23 | 5.90 |
| 36.6 | 6.07 | 6.63 | 6.75 | 6.94 | 6.29 | 5.89 | 5.65 | 5.82 | 5.32 | 5.20 | 5.12 | 5.24 | 5.91 |
| 36.8 | 6.08 | 6.64 | 6.76 | 6.95 | 6.31 | 5.90 | 5.66 | 5.83 | 5.33 | 5.21 | 5.13 | 5.25 | 5.92 |
| 37.0 | 6.09 | 6.66 | 6.77 | 6.97 | 6.32 | 5.91 | 5.67 | 5.84 | 5.34 | 5.22 | 5.14 | 5.26 | 5.93 |
| 37.2 | 6.11 | 6.67 | 6.79 | 6.98 | 6.33 | 5.92 | 5.68 | 5.85 | 5.35 | 5.23 | 5.15 | 5.27 | 5.94 |
| 37.4 | 6.12 | 6.68 | 6.80 | 6.99 | 6.34 | 5.93 | 5.70 | 5.86 | 5.36 | 5.24 | 5.16 | 5.28 | 5.96 |
| 37.6 | 6.13 | 6.70 | 6.81 | 7.01 | 6.36 | 5.94 | 5.71 | 5.87 | 5.37 | 5.25 | 5.17 | 5.29 | 5.97 |
| 37.8 | 6.14 | 6.71 | 6.83 | 7.02 | 6.37 | 5.96 | 5.72 | 5.88 | 5.38 | 5.26 | 5.18 | 5.30 | 5.98 |
| 38.0 | 6.15 | 6.72 | 6.84 | 7.03 | 6.38 | 5.97 | 5.73 | 5.89 | 5.39 | 5.27 | 5.19 | 5.31 | 5.99 |
| 38.2 | 6.17 | 6.73 | 6.85 | 7.05 | 6.39 | 5.98 | 5.74 | 5.91 | 5.40 | 5.28 | 5.20 | 5.32 | 6.00 |
| 38.4 | 6.18 | 6.75 | 6.87 | 7.06 | 6.40 | 5.99 | 5.75 | 5.92 | 5.41 | 5.29 | 5.21 | 5.33 | 6.01 |
| 38.6 | 6.19 | 6.76 | 6.88 | 7.07 | 6.41 | 6.00 | 5.76 | 5.93 | 5.42 | 5.30 | 5.22 | 5.34 | 6.02 |
| 38.8 | 6.20 | 6.77 | 6.89 | 7.08 | 6.43 | 6.01 | 5.77 | 5.94 | 5.43 | 5.31 | 5.23 | 5.35 | 6.03 |
| 39.0 | 6.21 | 6.79 | 6.90 | 7.10 | 6.44 | 6.02 | 5.78 | 5.95 | 5.44 | 5.32 | 5.24 | 5.36 | 6.05 |
| 39.2 | 6.22 | 6.80 | 6.92 | 7.11 | 6.45 | 6.03 | 5.79 | 5.96 | 5.45 | 5.33 | 5.25 | 5.37 | 6.06 |
| 39.4 | 6.24 | 6.81 | 6.93 | 7.12 | 6.46 | 6.04 | 5.80 | 5.97 | 5.46 | 5.34 | 5.26 | 5.38 | 6.07 |
| 39.6 | 6.25 | 6.82 | 6.94 | 7.13 | 6.47 | 6.05 | 5.81 | 5.98 | 5.47 | 5.35 | 5.27 | 5.39 | 6.08 |
| 39.8 | 6.26 | 6.83 | 6.95 | 7.15 | 6.48 | 6.06 | 5.82 | 5.99 | 5.48 | 5.36 | 5.27 | 5.40 | 6.09 |
| 40.0 | 6.27 | 6.85 | 6.96 | 7.16 | 6.49 | 6.07 | 5.83 | 6.00 | 5.49 | 5.37 | 5.28 | 5.41 | 6.10 |
| 40.2 | 6.28 | 6.86 | 6.98 | 7.17 | 6.50 | 6.08 | 5.84 | 6.01 | 5.49 | 5.37 | 5.29 | 5.42 | 6.11 |
| 40.4 | 6.29 | 6.87 | 6.99 | 7.18 | 6.52 | 6.09 | 5.85 | 6.02 | 5.50 | 5.38 | 5.30 | 5.43 | 6.12 |
| 40.6 | 6.30 | 6.88 | 7.00 | 7.20 | 6.53 | 6.10 | 5.86 | 6.03 | 5.51 | 5.39 | 5.31 | 5.44 | 6.13 |
| 40.8 | 6.31 | 6.89 | 7.01 | 7.21 | 6.54 | 6.11 | 5.87 | 6.04 | 5.52 | 5.40 | 5.32 | 5.45 | 6.14 |
| 41.0 | 6.32 | 6.91 | 7.02 | 7.22 | 6.55 | 6.12 | 5.88 | 6.05 | 5.53 | 5.41 | 5.33 | 5.46 | 6.15 |

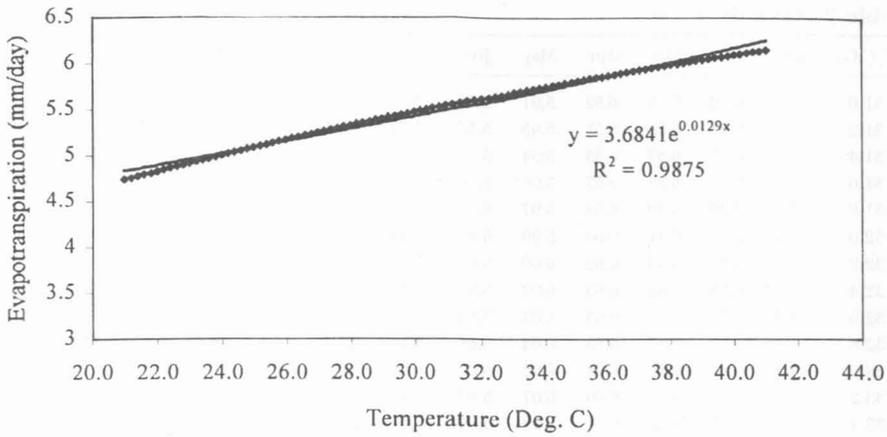


*Fig 4. Average variation of potential evapotranspiration with temperature*

## CONCLUSIONS

This paper describes methods used to calculate daily time series of free-surface or potential evaporation $E_p$ using the Penman equation, and potential evapotranspiration $ET_p$ using the Penman-Monteith equation without keeping any model calibration parameters. The long-term monthly averaged daily estimates of $E_p$ for different months were compared with the observed pan evaporations and more than 95% simulation results were achieved. Thus, these results can be interpreted as a validation of the $E_p$ model and can safely be used in the $ET_p$ model. The calculated $ET_p$ values are less than the calculated $E_p$ values by incorporating the surface resistance of the whole canopy. The surface resistance is less when more leaves are present since there are then more stomata through which transpired water vapor can diffuse. The results suggest that vegetation change resulting in increased canopy resistance decreases $ET_p$.

In order to investigate the sensitivity of $ET_p$, all the model equations containing temperature terms are set dependent of temperature and correlation between mean relative humidity and temperature is made. The $ET_p$ time series is perturbed changing monthly temperature from 21°C to 41°C with + 0.2°C increment. The results from the perturbations show that the $ET_p$ values increase towards increasing temperature for each month.


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## APPENDIX I: NOTATION

*The following symbols are used in this paper:*

$C_p$ = specific heat of air at constant pressure ($kJ.kg^{-1}.K^{-1}$);
$c_s$ = soil heat capacity (2.1 $MJ.m^{-3}.°C^{-1}$);
$d_s$ = estimated effective soil depth (m);
$E$ = vapor flux rate ($kPa.m.s^{-1}$);
$E_p$ = free-surface or potential evaporation (mm/day);
$ET_p$ = potential evapotranspiration (mm/day);
$e°$ = saturated vapor pressure of the air (kPa);
$e_d$ = mean actual vapor pressure of air at dew point temperature (kPa);
$G$ = soil heat flux ($MJ.m^{-2}day^{-1}$);
$h_c$ = mean height of the crop (m);
$k_s$ = a constant (dimensionless);
$n$ = actual number of hours of bright sunshine (h/day);

$N$ = possible maximum number of sunshine hours (h/day);
$P_a$ = air pressure (kg.m$^{-2}$ or kPa);
RH = relative humidity (%);
$R_a$ = extra-terrestrial radiation (MJ.m$^{-2}$day$^{-1}$);
$R_{nl}$ = net long-wave outgoing radiation (MJ.m$^{-2}$day$^{-1}$);
$R_s$ = short-wave solar radiation (MJ.m$^{-2}$day$^{-1}$);
$R_n$ = net radiation (MJ.m$^{-2}$day$^{-1}$);
$r_a$ = atmospheric vapor resistance (s.m$^{-1}$);
$r_s$ = vegetation canopy vapor resistance (s.m$^{-1}$);
$T_a$ = air temperature (°C);
$U_2$ = wind speed at 2m altitude (m/s);
$z$ = measurement height (m);
$z_0$ = surface roughness height (m);
$\alpha$ = surface albedo (dimensionless);
$\gamma$ = psychrometric constant (kPa.°C$^{-1}$);
$\Delta$ = gradient of saturation vapor pressure-temperature curve (kPa.°C$^{-1}$);
$\lambda$ = latent heat of vaporization of water (MJ.kg$^{-1}$);
$\sigma$ = Stefan-Boltzmann constant (4.903 x $10^{-9}$ MJm$^{-2}$ K$^{-4}$ day$^{-1}$); and
$\rho_a$ = air density (kg.m$^{-3}$)