Validation in an Arid Area of an Algorithm for the Estimation of Daily Solar Radiation

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ABSTRACT

The Thornton–Running algorithm to estimate daily global radiation was tested at a site in a coastal desert of the eastern Mediterranean. In this algorithm three factors are multiplied in order to compute the daily global radiation: the total daily extraterrestrial radiation impinging on a horizontal plane, the maximum daily total atmospheric transmittance possible on days with clear skies ($T_{t,\max}$), and the realized proportion of $T_{t,\max}$ for days during which the sky is not clear ($T_{f,\max}$).

Estimates of $T_{t,\max}$ compared very well with measured values while this was not the case for $T_{f,\max}$. A good correlation was, however, obtained between predicted and measured values of daily global radiation with a noticeable underprediction of global radiation when measured values exceeded 20 MJ m^{-2}. A regression analysis showed that errors in the estimated global radiation were linearly related to errors in $T_{f,\max}$. Analysis of the data used in this study indicated that for the conditions prevailing in the area it was not necessary to introduce a correction factor for rainy days.

The possibility of using the saturated vapor pressure at minimum daily temperature in lieu of the actual measured daily averages of saturated vapor pressure is evaluated, and the results indicate that this approximation is reasonable and does not noticeably affect the estimation of global radiation.

A systematic underestimation of daily Penman's potential evapotranspiration (PET) during the dry summer period was observed when the computation of PET was carried out using the estimated values of global radiation instead of the measured ones. During this period a further underestimation of PET was observed when the latter was computed using the saturated vapor pressure at minimum daily temperature instead of measured daily values in all the equation terms. This underestimation was not noticeable during the winter period.

1. Introduction

Solar radiation is the driving force for a very large number of the physical and biological processes that take place on the surface of our planet and can be directly measured. However, the density of meteorological stations at which incoming solar radiation is routinely measured is not high and is commonly very low in some of the less populated and underdeveloped areas (Thornton and Running 1999). These areas are, however, frequently the focus of regional development programs for which estimates of evaporation from free water surfaces and water use by vegetation (natural and/or agricultural crops) are necessary. Direct observations of evaporation in either case are extremely rare and the use of models to obtain regional estimates of water losses by direct evaporation or transpiration becomes unavoidable. The most frequently used models are based on estimating the potential evapotranspiration (PET) through the approximate energy balance approach of Penman or its derivations (Brutsaert 1982). Incoming daily solar radiation is an essential and critical input for such models (Brutsaert 1982; Cooter and Dhakhwa 1996; de Bruin and Stricker 2000). Estimates of half-hourly and hourly fluxes of global radiation (total incident shortwave radiation on a horizontal plane) can be computed using models that rely on data provided by geostationary satellites (Illera et al. 1995; Stewart et al. 1999). Even though the precision of the estimates for daily values for moderately sized areas may be adequate (Stewart et al. 1999), the computational procedures are rather complicated. A more serious limitation for the use of this approach, in the context of estimating watershed water

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balances (for the prediction of fluvial dynamics or groundwater recharge), lies in the fact that historical records of PET, and hence of daily integrals of global radiation, are required (Lindsay and Farnsworth 1997). The latter are also necessary to estimate required water volumes during the planning stages of new irrigation schemes.

Daily integrals of global radiation can be estimated using formulae based on sunshine duration (Brutsaert 1982; Chegaar and Chibani 2001; Nguyen and Pryor 1997; Togrul et al. 2000; Lin et al. 1999; Tadros 2000). These types of models have been shown to be better predictors than other models based on more commonly registered meteorological parameters (Osterle 2001; Ertekin and Yaldiz 2000; Meza and Varas 2000), but sunshine duration is not routinely measured and the usefulness of formulae based on this parameter is therefore rather limited.

The only two meteorological parameters that are routinely measured at a large number of meteorological stations are temperature and precipitation. A model to predict global radiation based on temperature and precipitation is therefore of great interest and could have wide application. Bristow and Campbell (1984) presented a model that predicted global radiation based on the daily temperature amplitude. It performed satisfactorily when tested against data obtained from three stations located in the temperate climate zone of the United States. This model was tested in other areas and found to be robust (Goodin et al. 1999; Meza and Varas 2000). One of the drawbacks of the model is that a fitting parameter of the model appeared to be site specific. This parameter was recognized as being related to the global radiation measured during clear days and was obtained by regressing measurements of estimated radiation data. Thornton and Running (1999) presented an improved model (TR model henceforth) based on the Bristow and Campbell (1984) approach. They proposed a different parameterization for the coefficients and described a procedure for computing the global radiation during clear days. The Solar and Meteorological Surface Observational Network (SAMSON) database that covers the continental United States was used to derive the model parameters as well as to test model predictions. The resulting model (which requires values of precipitation, daily maximum and minimum temperature, and daily average near-surface water vapor pressure) predicted daily global radiation satisfactorily. The model performed well over a large variety of climatic zones and is particularly appealing because there is no need for further calibration or introduction of additional empirical coefficients, that is, it could be used with confidence in areas for which no radiation measurements are available. However, before doing so it is necessary to validate the algorithm using a completely independent dataset from a different region. Moreover, it would be of interest to carry out the validation study in an area in which there are few radiation-measuring stations. The Negev Desert of Israel is a coastal desert with a very small number of radiation-measuring stations and is representative of large areas in the Near East.

Our objective was to test the TR model and its parameters in the Negev Desert and ascertain the effect the errors in radiation estimates have on the computation of PET.

2. Brief description of the TR (Thornton–Running 1999) model

The daily global radiation (R_{gh}) is computed using

$$R_{gh} = R_{pot} T_{t,\max} T_{f,\max}, \tag{1}$$

where R_{pot} (MJ m^{-2} day^{-1}) is the total daily extraterrestrial radiation impinging on a horizontal plane, $T_{t,\max}$ is the maximum daily total atmospheric transmittance possible on days with clear skies, and $T_{f,\max}$ is the realized proportion of $T_{t,\max}$ for days during which the sky is not clear. The latter is parameterized for any day of the year as

$$T_{t,\max} = \left[\frac{\sum_{s=sr}^{st} R_{pot,s} \cdot \tau_{0,\mathrm{nadir,dry}}^{(p_z/p_o)\cdot m_\theta}}{\sum_{s=sr}^{st} R_{pot,s}} \right] + \alpha e, \tag{2}$$

where the subscript s stands for solar time and the sums are carried out between sunrise (sr) and sunset (st), τ_0 is the instantaneous transmittance at reference elevation (constant and equal to 0.87), p_z is the surface air pressure at height z and p_0 the surface air pressure at reference elevation, m_θ a correction for optical air mass dependent on zenithal angle θ (Gates 1980), α a slope parameter (equal to -6.1×10^{-5} Pa^{-1}) and e near-surface water vapor pressure (Pa).

The value $T_{f,\max}$ is computed for each day of the year as

$$T_{f,\max} = [1 - 0.9 \times \exp(-B\Delta T^C)], \tag{3}$$

where ΔT is the daily range of temperature, C a constant (equal to 1.5), and B computed as

$$B = b_0 + b_1 \exp(-b_2 \overline{\Delta T_{30}}), \tag{4}$$

where b_0, b_1, and b_2 (0.031, 0.201, and 0.185 respectively) are empirical coefficients and $\overline{\Delta T_{30}}$ is a 30-day average (which includes the day for which computations are carried out and the preceding 29 days).

3. Site description

The Negev is characterized by hot summers and cold winters during which most of the rainfall occurs. Similar conditions prevail along the coastal areas of North Africa. The ''Koeppen and Geiger'' climatic zone definition for the region where the measurements were performed is BWks (Evenari et al. 1982). Two different synoptic conditions leading to cloudiness and precipitation are typical for the Negev:

- Low pressure systems in the Mediterranean basin, usually associated with an extensive cloud cover, that produce a relatively low-intensity rainfall over large areas.
- The Red Sea trough, typical for spring and autumn, which results in very localized rainstorms of high intensity and short duration.

An additional feature that frequently affects radiation patterns during the transitional seasons in the Negev region is the chamsin—a hot, dry wind coming from either the Arabian Peninsula or the eastern Sahara. During the chamsin, very low humidity conditions prevail together with high dust concentrations in the lower atmosphere and a relatively small difference between day and night temperatures (Evenari et al. 1982).

4. Materials and methods

Meteorological data recorded in Sde Boker, Israel (30°51′N, 34°46′E; 470 m AMSL) from 1996 to 1998 by the Desert Meteorological Unit of the Blaustein Institute for Desert Research was used in this study. Wet- and dry-bulb temperature, global radiation, and wind speed were continuously monitored, and hourly maximum, minimum, and average values registered for each parameter. Maximum, minimum, and daily averages were derived from the hourly values. Global radiation (R_{gh}) was monitored with a precision spectral pyranometer (Eppley precision spectral pyranometer, model PSP[1]).

5. Computational procedures

The measured daily transmittance was computed as

$$T^{meas} = \frac{R_{gh}^{meas}}{R_{pot}}, \qquad (5)$$

where R_{gh}^{meas} is the measured daily global radiation (MJ m^{-2}) and R_{pot} (MJ m^{-2}) was computed as detailed in Gates (1980). We divided the data for each of the 3 yr into thirty-six 10-day periods (neglecting the last 5 days). For each 10-day period the highest daily T^{meas} among the data available for the 3 yr was selected and set as $T_{t,max}^{meas}$ for that 10-day period. In order to be able to compare the measured to the estimated values, the $T_{t,max}$ computed using (2) were averaged for each of the thirty-six 10-day periods.

$T_{f,max}^{meas}$ was computed for each day as follows:

$$T_{f,max}^{meas} = \frac{R_{gh}^{meas}}{R_{pot} \times T_{t,max}^{meas}} \qquad (6)$$

with the $T_{t,max}^{meas}$ corresponding to the relevant 10-day period being used. The corresponding $T_{f,max}$ was computed for each day using (3).

Bristow and Campbell (1984) suggested a correction to (3) in order to account for a decreased radiation load during rainy days. A preliminary inspection of the data did not indicate that a correlation existed between rainy days and ΔT or R_{gh} values. Large rain events were possible even on days with low cloud cover (measured transmittance >0.68), which is typical during high-intensity convective storms of relatively short duration (see also earlier: Red Sea trough). Conversely, during the winter season we also found periods of days with low radiation loads (cloudy days with a measured transmittance <0.5) without rain. In view of these facts we used Eq. (3) without modifications for rainy days.

Penman's potential evapotranspiration was computed using (7) (Brutsaert 1982) and neglecting the daily soil heat flux:

$$\begin{aligned} PET_{m,e} = {} & [s/(s + \gamma)] \times NR_{m,e} \\ & + [\gamma/(s + \gamma)] \times 0.26 \\ & \times (1 + 0.54 \times u_2)(e_a^* - e_a) \text{ (mm day}^{-1}\text{)}, \end{aligned} \qquad (7)$$

where subscripts m and e denote the use of measured or estimated global shortwave radiation, and

- u_2, average wind speed measured at 2-m height (m s^{-1});
- γ, psychrometer constant (mb °C^{-1});
- s, slope of the saturated vapor pressure curve (against temperature) at average daily dry-bulb temperature (mb °C^{-1});
- e_a^*, saturated vapor pressure at average daily dry-bulb temperature (mb);
- e_a, actual average daily vapor pressure (mb); and
- $NR_{m,e}$, net radiation [mm day^{-1}, to make it compatible with the units of the second term in (7)] and computed as

$$NR_{m,e} = \left\{ G(1 - \rho) + D_l \sigma T_a^4 \left[\left(\frac{e_a}{T_a} \right)^{1/7} - 1 \right] \right\} \times \frac{1000}{L_e \rho_w}, \qquad (8)$$

with $G = R_{gh}^{meas}$ or R_{gh} corresponding to subscripts m and e, respectively (J m^{-2});

- ρ, albedo of water (=0.05);
- D_l, 86 400 s;
- σ, Boltzmann coefficient (=5.7 10^{-8} W m^{-2} K^{-4});
- T_a, absolute average daily temperature (K);
- L_e, latent heat of vaporization of water (J kg^{-1}); and
- ρ_w, density of water (kg m^{-3}).

[1] Mention of trademark is for the benefit of the reader only and does not imply endorsement by the authors.

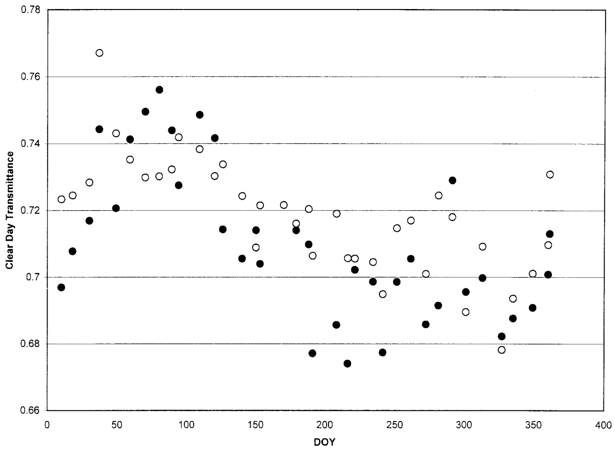

FIG. 1. Seasonal change of maximum measured 10-day period transmittance ($T_{t,\max}^{\mathrm{meas}}$, filled circles) and corresponding averaged 10-day period values of computed clear day transmittance ($T_{t,\max}$, empty circles) as a function of day of year (DOY).

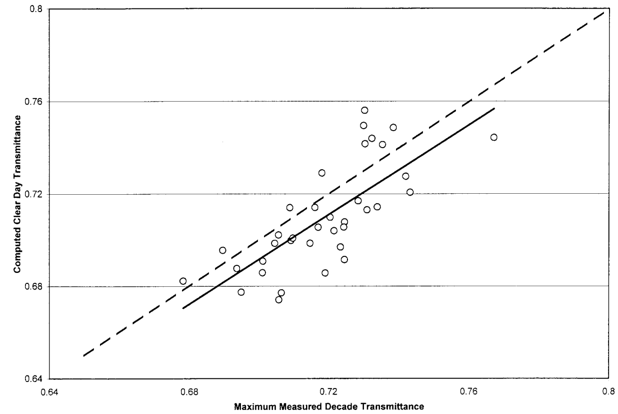

FIG. 2. Ten-day average of computed clear day transmittances ($T_{t,\max}$) as a function of corresponding maximum measured 10-day period transmittance ($T_{t,\max}^{\mathrm{meas}}$). Solid line is the regression line and a 1:1 line (dashed) is included for reference. Statistics are presented in Table 1.

The Priestley and Taylor (1972) PET was computed using

$$\mathrm{PET\_PT} = \alpha \frac{s}{s + \gamma} \mathrm{NR}_m \qquad (9)$$

with $\alpha = 1.26$.

6. Results and discussion

The measured and computed maximum transmittances are presented in Fig. 1. Our data does not exhibit the same seasonal trend with a clear peak in midsummer as does the data presented by Thornton and Running (1999) for stations located in arid zones. Nevertheless, the computed values predict the seasonal changes remarkably well, particularly the peak during the month of March. The linear regression between computed and measured maximum transmittances is presented in Fig. 2, and the corresponding statistics are in Table 1.

In Fig. 3 $T_{f,\max}$ and $T_{f,\max}^{\mathrm{meas}}$ are plotted as a function of the corresponding daily temperature amplitudes. A large fraction of the measured transmittances are in the range 0.8–1, but they show no clear dependence on daily temperature amplitude. It is particularly noteworthy that relatively clear sky days ($T_{f,\max}^{\mathrm{meas}} > 0.9$) occurred in a large number of instances in which relatively small temperature amplitudes (8°–12°C) were recorded. Conversely, low measured transmittances ($T_{f,\max}^{\mathrm{meas}} < 0.8$) were registered for days with large temperature amplitudes (12°–22°C), albeit a smaller number than in the former case. Notwithstanding these deviations, the trend of the bulk of the transmittances appears to be reasonably well described by Eq. (3).

The computed and measured daily integrals of global radiation are presented in Fig. 4. The regression is highly significant, as well as the intercept and the slope (Table 1). Daily global radiation is underestimated whenever the measured values exceed 20 MJ m^{-2}. In order to evaluate the impact of the lack of correction for rainy days, we segregated the data into two groups according to the occurrence of rainfall. The slopes and the intercepts of both groups (data not presented) were not significantly different, which bears out our contention that there is no need to include a correction for rainy days.

The relative errors in $R_{\mathrm{gh}}[(R_{\mathrm{gh}} - R_{\mathrm{gh}}^{\mathrm{meas}})/R_{\mathrm{gh}}^{\mathrm{meas}}]$ are plotted in Fig. 5 against the corresponding relative errors in transmittances $[(T_{f,\max} - T_{f,\max}^{\mathrm{meas}})/T_{f,\max}^{\mathrm{meas}}]$ and the regression results (Table 1) clearly indicate that the source

TABLE 1. Summary statistics for the linear regressions depicted in the various graphs. (ns = not significant; * = $p < 0.05$; ** = $p < 0.005$).

Figure no.	Dependent parameter	Independent parameter	Intercept	Slope	r^2	Significance of model (F test)
2	$T_{t,\max}$	$T_{t,\max}^{\mathrm{meas}}$	0.023$^{\mathrm{ns}}$	0.9527**	0.447	**
4	R_{gh}	$R_{\mathrm{gh}}^{\mathrm{meas}}$	2.89**	0.8236**	0.8479	**
5	Relative error in R_{gh}	Relative error in $T_{f,\max}$	−0.02766$^{\mathrm{ns}}$	−0.98289**	0.981	**
6	PET_e	PET_m	0.306**	0.899**	0.939	**
7	PET^e	PET_e	0.242**	0.908**	0.971	**

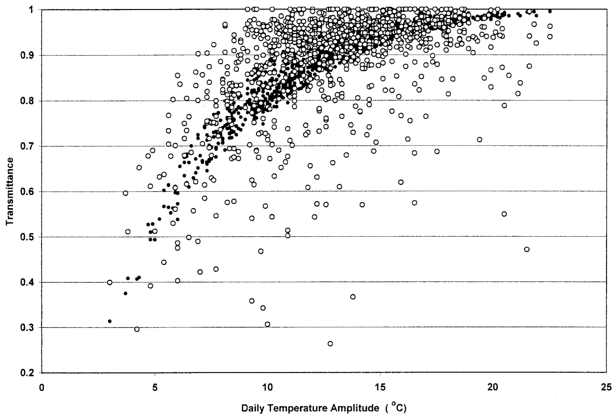

FIG. 3. Computed ($T_{f,\max}$, empty circles) and measured ($T_{f,\max}^{\text{meas}}$, filled circles) values of realized proportions of clear day transmittances plotted against the corresponding daily temperature ranges.

of the bias in the correlation between measured and computed global radiation is $T_{f,\max}$.

Thornton and Running (1999) state that vapor pressure is not usually measured, and argue that the lack of this parameter could be a serious limitation to the implementation of their model. We evaluated the possibility of using the saturated vapor pressure at minimum temperature in lieu of the actual measured daily average even though this approach has been questioned (Kimball et al. 1997). The coefficients of the regression between computed R_{gh} using the saturated vapor pressure at minimum temperature and measured global radiation (intercept = 3.2765, slope = 0.7291, and r^2 = 0.8407) are very similar to those obtained when using the measured vapor pressure (Table 1, Fig. 4), and the resulting graph (not presented) is indistinguishable from Fig. 4.

In order to ascertain the impact that errors in the estimation of global radiation may have on water balances or irrigation requirements, we computed daily potential evaporation using measured and estimated global

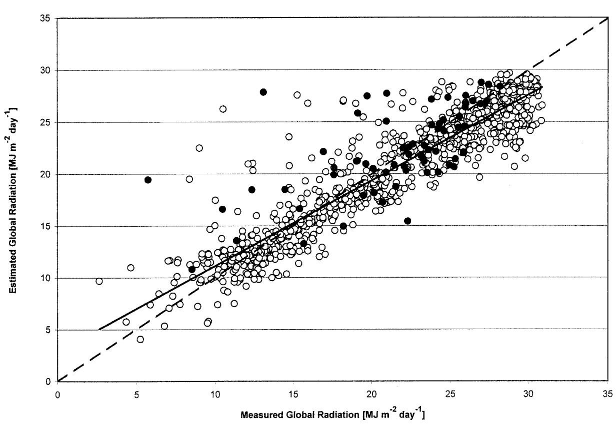

FIG. 4. Estimated global radiation (R_{gh}) as a function of measured global radiation. Filled circles indicate days for which rainfall was recorded. Solid line is the regression line and a 1:1 line (dashed) included for reference. Statistics are presented in Table 1.

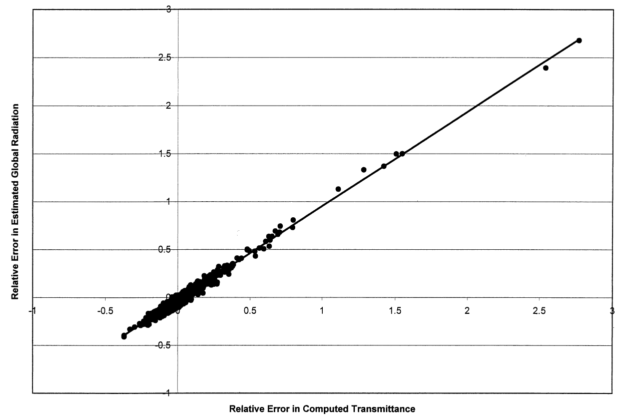

FIG. 5. Relative error in the estimated global radiation (R_{gh}) as a function of the relative error in computed $T_{f,\max}$ (detailed explanation in text). Solid line is the regression line and statistics are presented in Table 1.

radiation. Results are presented in Fig. 6 and an extremely good correlation is observed. A slight underestimation of PET due to the use of estimated global radiation is evident for values of PET above 7–8 mm day^{-1}.

The lack of daily surface vapor pressure data would affect as well the computations of PET through the computation of NR [Eq. (8)] and the second term in (7). In Fig. 7 PET^e, computed using the saturated vapor pressure at minimum temperature instead of the measured daily average vapor pressure in all relevant parameters [R_{gh}, NR, and the second term in Eq. (7)], is compared to PET$_e$. The correlation of both quantities is very good and only a slight underestimation is evident for the highest values of PET. These results suggest that in arid areas that have meteorological characteristics similar to those of the present study, the lack of measured water vapor pressure may be overcome by replacing it with the saturated vapor pressure at minimum daily temperature without seriously affecting the quality of the estimates.

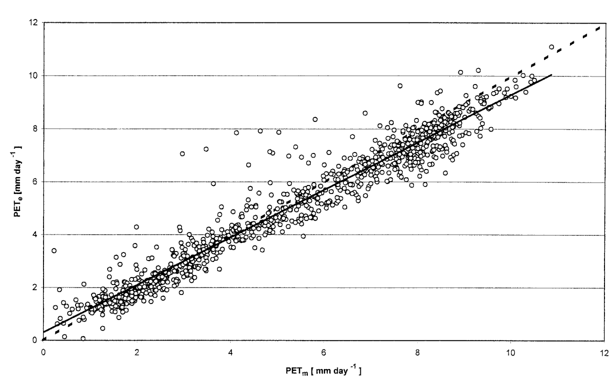

FIG. 6. Penman's PET computed using estimated global radiation (PET$_e$) as a function of Penman's PET computed using measured global radiation (PET$_m$). Solid line is the regression line and a 1:1 line (dashed) included for reference. Statistics are presented in Table 1.

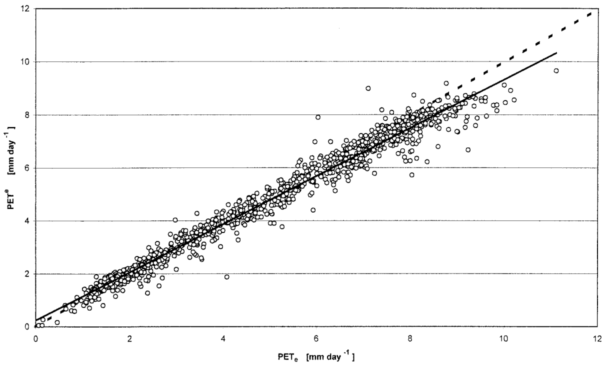

FIG. 7. Penman's PET computed using saturated vapor pressure at min daily temperature instead of measured daily averaged vapor pressure (PET^e) as a function of PET_e. For details of computation see text. Solid line is the regression line and a 1:1 line (dashed) included for reference. Statistics are presented in Table 1.

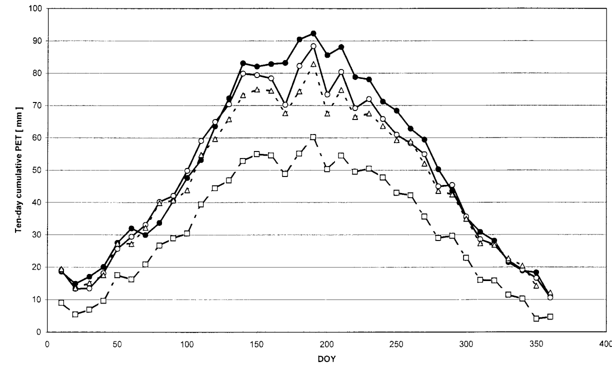

FIG. 8. Ten-day cumulative values of PET_m (filled circles), PET_e (empty circles), PET^e_e (empty triangles), and PET_PT (empty squares) for Sde Boker, Israel, during 1997. For full description of computational procedures see text.

Thornton et al. (2000) reported similar findings when they used the TR algorithm to estimate incoming global radiation over an altitude gradient in Austria. The very different weather patterns at both sites (Austria and the Israeli Negev) suggest that the proposed substitution may be a valid one for a wide range of climatic conditions.

It is quite common to utilize 10-day cumulative values of PET for watershed water balances and for the planning of large-scale irrigation schemes. We computed 10-day cumulative values of PET_m, PET_e, and PET^e. In Fig. 8 results are presented for 1997, the year for which the largest differences of PET_e and PET^e with PET_m were found for the summer months [day of year (DOY) 120–270]. Practically no differences between the three quantities are evident during the winter period of 1997, as is also the case for 1996 and 1998 (not shown). During the dry summer period PET_e underestimated PET_m by a total of 95 mm (83 and 32 mm for 1996 and 1998, respectively) while PET^e underestimated PET_m by 155 mm (151 and 82 mm for 1996 and 1998, respectively). For illustrative purposes we present in Fig. 8 PET_PT, which underestimates PET slightly in winter and very severely during the dry summer months.

The results presented indicate that the estimation of $T_{t,\max}$ by the TR model is better than the estimation of $T_{f,\max}$. Nevertheless, the computed radiation is well correlated with the corresponding measured radiation. The use of saturated vapor pressure at minimum temperature in lieu of the actual measured daily average did not affect the quality of global radiation estimates, even though the correlation between measured and estimated average daily vapor pressures (data not presented) shows a large spread. The reason for this apparent contradiction is the fact that the main determinant of errors in the estimated global radiation is $T_{f,\max}$ for whose computation water vapor data are not required.

Thornton and Running (1999) reported a negative bias for the stations located in arid environments. Our results confirm this fact and additionally provide important information on the seasonality of this trend. The value R_{gh} underestimates global radiation at high irradiances, which leads to the underestimation of PET during summer. However, in the area in which the data was collected, rainfall occurs during winter and it is during this period that catchment water balances would be carried out, as the soil is dry and transpiration of natural vegetation negligible during summer. The estimates of PET using measured and estimated incoming radiation fluxes during this period are similar, and indicate that the TR model can be used with confidence. Moreover the use of saturated vapor pressure at minimum daily temperature has no noticeable effect on 10-day cumulative values of PET, and this substitution can be used with confidence during the winter period.

On the other hand, PET is underestimated during the summer period when estimated R_{gh} is used. The use of saturated vapor pressure at minimum daily temperature slightly increases the underestimation. These results cast some doubts about the possibility of using this approach for the estimation of the irrigation needs of crops, even though it is clear from our computations that this approach is always better than the use of the Priestley–Taylor equation.

7. Conclusions

The Thornton–Running model for estimating global radiation was developed using a dataset that covered the continental United States. In this study the model was tested in the Negev, a desert in the southeastern Mediterranean region, without altering or calibrating any of the coefficients of the model. The results from the TR model were well correlated with measured values for the 3 yr studied, but slightly underestimated the real values at high irradiances. Substitution of measured daily average vapor pressure by saturated vapor pressure at daily minimum temperature did not significantly affect the results of the estimation.

PET computed using estimated global radiation was similar to the PET computed using measured global radiation during the winter months but underestimated it during the dry summer months. The use of the previously mentioned substitution in the computation of PET resulted in an additional underestimation, but proved to be a far better approximation than the use of the Priestley–Taylor equation.

The Thornton-Running model appears to be a very good tool for the estimation of global radiation in arid areas, an essential input for hydrological studies.

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