EFFECT OF SOLAR RADIATION ON THE CROPS EVAPOTRANSPIRATION IN EGYPT

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ABSTRACT

Accurate estimation of crops water needs is essential for irrigation scheduling and water savings. The Penman-Monteith equation is frequently used for calculating the reference evapotranspiration ET_O and hence the crop water requirements. Reference evapotranspiration reflects the impact of weather condition to the evaporation and transpiration, and it is the basic data to crop irrigation and water distribution in irrigation district. This equation contains many parameters that depend mainly on the solar radiation. In this work, the effect of global solar radiation on the daily mean value of ET_O is investigated. For this reason, a MATrix LABoratory MATLAB computer program is constructed and used for the computation of ET_O at the daily mean solar radiation on the river Nile Delta of Egypt. Comparison of results calculated from alternative formulae used to calculate solar radiation data and that obtained from the National Aeronautics and Space Administration (NASA) website on this area is carried out. Results are shown in graphical form to be an accurate and quick method for estimating the water requirements for different crops in this area.

Keywords: Solar radiation, Crops evapotranspiration, Egypt

1. INTRODUCTION

Knowledge of the exact amount of water required by different crops in a given set of climatic conditions of a region is of great help in planning of irrigation scheme, irrigation scheduling, effective design and management of irrigation system. The growing agricultural needs and wrong irrigation policy brought the world to a great water crisis in the next few years. The irrigated agriculture requirements are estimated by about 70% of the total human fresh water resources available all over the world, FAO Bruinsma [1]. The absence of appropriate irrigation management and wrong water estimation for different crops in Egypt are probably the main reasons of increasing the irrigated agriculture water use to about 85% of the total river Nile water share, 55.5 milliard m^3, Ismail [2].

The increased pressure on irrigated agriculture to reduce its water use makes irrigation efficiency even more important. Irrigation professionals need to know the latest thinking and information on the calculation of crop water requirements. The moves towards micro irrigation, precision irrigation and deficit irrigation requires more accurate estimation of crop water needs. New crop growth and water use calculation tools are becoming available that can optimize yield and water use.

Transpiration is the evaporation from the plant through the leaves stomata. Both evaporation and transpiration occur in response to climate demand. Evapotranspiration is greatest on hot, sunny and dry days and lowest on cool, cloudy and humid days. The irrigation requirement for any crop is the amount of water that must be applied to meet the crop's evapotranspiration (ET) needs and avoid the plant water stress. Plant water stress will occur if ET is limited because water is not available to plants. Water stress will occur quickest on high climate demand days. Water stress is avoided by rainfall or by irrigating to provide a crop with the water needed for evaporation and transpiration. The amount of ET includes water that is needed for both evaporation and transpiration. Evaporation occurs from all wet surfaces, including soil, water and plants. The amount of evaporation in these three sources depends mostly on the amount of energy available for transformation of water from liquid to vapor form. This energy depends mainly on solar energy falling on the earth’s surface.

Evapotranspiration is a key component for terrestrial ecosystems not only for its energy balance, but also for its mass balance. Since surface energy and water exchange are two key processes that can determine the characters of environment to a large extent, researches on ET are focused by scientists around the world, especially on water balance and regional sustainable water management practices.

Estimates of actual ET are important for understanding regional water balance, irrigation requirements, atmospheric boundary layer stability and weather forecasting. But, it is difficult to measure ET directly, and in most applications ET is estimated using models. Moreover, ET is the process by which water is released into the air by evaporation from the soil and transpiration from plant surfaces. Reliably quantifying ET is not only an important task for agriculture managers who deal with water resources management, but also a challenge to scientists working in agriculture, because ET is difficult to directly measure and must be estimated through theoretical modeling.

Evaporation can be classified into potential evaporation and actual evaporation. The potential evaporation is defined as the amount of evaporation that would occur if sufficient water sources were available. On the other hand, the actual evaporation is the amount of water which is evaporated in a normal day. The potential evaporation is the maximum value of the actual evaporation. Transpiration includes the vaporization of liquid water contained in plant tissues and vapor transfer to the atmosphere Hongjie et al. [3] and Kalluri et al. [4]. Actual evapotranspiration for a crop can be calculated from the crop coefficient (K_c) multiplied by the reference evapotranspiration (ET_O) Islam [5]. Crop coefficients can be evaluated from land use maps and the cropping calendar. Land use maps show the types of crops in the study area while the cropping calendar presents the growth stage of crops. Then, the value of the crop coefficient depends on the type and growth stage of the crop. On the other hand, ET_O can be estimated by using meteorological parameters such as temperature, humidity, wind speed and net solar radiation. These parameters are the elements of the FAO Penman-Monteith method that is now recommended as the standard method for the definition and computation of the reference evapotranspiration. However, before this FAO

Penman- Monteith method became the accepted standard, many methods were used for the estimation of ET_O. These included the formulae of Penman [6], Monteith [7], Priestly and Taylor [8] and Hargreaves and Samani [9].

To obtain ET a reference evapotranspiraiton ET_O is first estimated through a calibrated ET_O model, and then the ET_O model is modified by a crop coefficient (K_c) to estimate actual ET. Also, evapotranspiration is one of the most important components because it represents a loss of usable water from the hydrological supply for agriculture, natural resources and municipalities. Evaporation is the primary process of water transfer in the hydrological cycle. The water is transformed into vapor and transported into the atmosphere.

The FAO Penman-Monteith method is the most suitable formula to calculate the reference evapotranspiration, because it uses many factors which impact the ET_O calculation Allen et al. [10], Droogers and Allen [11] and Popova et al. [12]. For this reason, ET_O in this research was obtained by the FAO Penman-Monteith method. Reference evapotranspiration is variable both spatially and temporally. The variability in ET_O is affected by principal weather parameters such as solar radiation, air temperature, humidity and wind speed. These parameters can be recorded by weather station data and computed by the equation of the FAO irrigation and Drainage Paper No. 56 Allen et al. [10].

Evapotranspiration process is determined by the amount of existing energy for water evaporation. The main source of energy turning water into vapor is solar radiation. Solar radiation absorbed by atmosphere and heat radiated by the earth increase air temperature. Physical heat of the air transmits energy to plants and controls evapotranspiration rate. Under sunny warm weather water losses for evapotranspiration are more than under cool and cloudy weather. Moreover, since sun and air energy is the main driven force of water evaporation, difference between water vapor pressure at evaporating surface and in the air is decisive factor of vapor transfer. Well wetted fields in dry arid regions require huge amount of water due to excessive energy and drying strength of atmosphere. In humid tropic regions, in spite of high energy, high air humidity reduces need in evapotranspiration. In this environment air is close to saturation by vapor so less additional water is accumulated and evapotranspiration is less compared with arid regions.

Global solar radiation on the Earth’s surface strongly controls the evaporation from the plants and soil. Small changes in solar radiation may have considerable effect on the calculated value of ET_O, Llasat and Snyder [13]. Solar radiation is usually measured by pyranometers which are in any case expensive and fragile devices. Small variations in solar radiation cannot be captured by pyranometers. It can be assumed that remotely sensed solar irradiation should be useful for ET_O estimation. On the other hand, solar radiation data are not readily available from national observatories, especially in Egypt. These data depend mainly on the latitude and geographical situation of the concerned area. Therefore, several correlations for many places worldwide are available in literature. In this work, the most frequently used of these correlations are considered, Meinel and Mainel [14], Duffie and Beckman [15] and Hinrichsen [16]. The sensitivity of the Penman-Monteith reference evapotranspiration to key climatic variables in the Changjiang (Yangtze River) basin is studied by Gong et al. [17]. They concluded that the relative humidity was the most sensitive variable, followed by solar radiation, air temperature and wind speed. Bois et al. [18] reported that calculating ET_O by Penman-Monteith is more sensitive to solar radiation in south France.

The objective of this research work is to investigate the influence of solar radiation estimated from different models on the value of ET_O in the Delta zone of Egypt. Most of the Egyptian agriculture activities are concentrated in this area. The results of different alternative models for solar radiation estimation and that obtained from the National Aeronautics and Space Administration (NASA) website [19] at the latitude of about 31°N and longitude of 31° E are used. The final target of this work is to help the decision maker to decide and use the most suitable model for more accuracy.

2. MATERIALS AND METHOD

Penman-Monteith combination method is one of the most accurate methods to evaluate ET_O at different time steps. A standardization of this method has been proposed by the Food and Agriculture Organization (FAO), Allen et al. [10]. It is known as FAO-56 Penman-Monteith application, and it can be considered as a worldwide standard. The daily average reference evapotranspiration (ET_O) is given in (mm/day) according this equation as,

$$ET_O = \frac{0.408\ \Delta\ (R_n - G) + \gamma \frac{900}{T + 273} U_2 (e_s - e_a)}{\Delta\ +\ \gamma\ (1 + 0.34\, U_2)} \tag{1}$$

Where, R_n is the net solar radiation at the crop surface (MJ/m^2 day),
G soil heat flux density (MJ/m^2 day),
T mean daily air temperature at 2 m height (°C),
U_2 wind speed at 2 m height (m/s),
e_s saturated air vapor pressure (kPa),
e_a The actual air vapor pressure (kPa),
Δ slope of saturated air vapor pressure curve (kPa/°C), and
γ is the psychrometric constant (kPa/°C).

The psychrometric constant, γ is given by,

$$\gamma = \frac{C_p P}{\varepsilon \lambda} \tag{2}$$

Where, P is the atmospheric pressure = 101.3 (kPa),
C_p specific heat at constant pressure = 1.005 (kJ/kg °C),
ε ratio of water vapor molecular weight to dry air = 0.622, and
λ is the latent heat of vaporization (MJ/kg) given by Harrison [20] as,
$(\lambda = 2.51 - 2.361 \times 10^{-3}\ T)$

Substituting in equation (2), (γ) can be expressed as,

$$\gamma = 1 / (15.33517 - 0.014425\ \ T) \tag{3}$$

The air saturation vapor pressure (e_s, kPa) can be obtained from the relationship correlated by Allen et al [10] as,

$$e_s = 0.6108 \exp\left(\frac{17.27\ T}{T + 237.3}\right) \tag{4}$$

The slope of air saturation vapor pressure curve (Δ, kPa/°C) can also be obtained in terms of the mean air temperature (T, °C) as given by Murray [21] in the following formula,

$$\Delta = \frac{4098\ \left[0.6108\ \exp\left(\frac{17.27\ T}{T + 237.3}\right)\right]}{(237.3\ + T)^2} \tag{5}$$

The actual vapor pressure in the atmospheric air (e_a) can be obtained by substituting the dew point temperature (T_{dew}) in equation (4). Most of the Egyptian agriculture activities are concentrated in the Nile Delta of Egypt. Therefore, this research work is concerned in the central part of this area (with Latitude 31°N and longitude 31°E). The average meteorological data over 10 years (from 1995 to 2005) obtained from **NASA** website [19] is shown in Table (1).

Table (1) Meteorological data at L=31° N and 31° E, NASA [19].

Year 1995-2005	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
T_{min}, °C	11.83	11.10	12.09	14.31	17.29	20.81	23.33	24.08	23.05	20.56	17.29	13.78
T_{max}, °C	17.78	17.64	19.20	21.94	24.73	27.72	30.51	30.50	28.72	25.52	22.40	19.29
T, °C	14.58	14.24	15.49	18.02	20.82	23.99	26.54	26.92	25.62	22.86	19.69	16.38
T_{dew}, °C	7.11	6.95	8.03	9.54	12.78	16.24	18.08	18.95	17.75	15.67	12.39	8.56
U_2 (m/s)	4.80	5.08	4.88	4.44	4.30	4.19	4.29	4.36	4.42	4.43	4.28	4.69
k_t	0.68	0.67	0.70	0.71	0.71	0.71	0.69	0.70	0.69	0.67	0.66	0.65
R_h, MJ/m^2.day	11.23	13.82	18.72	22.86	26.82	29.05	27.68	25.52	22	16.56	12.38	9.94

Solar Radiation

Neglecting the reflection component, the hourly global solar radiation on a horizontal surface, R_h in the clear sky model is given by Meinel and Mainel [14] as,

$$R_h = R_a\ (0.7)^{m^{0.678}} \tag{6}$$

Where, R_a is the extraterrestrial irradiance on a horizontal surface given by Markvart and Kreider [22] as,

$$R_a = 1.367\left[1 + 0.033\cos\left(\frac{2\pi J}{365}\right)\right] \sin\alpha \tag{7}$$

and, m is the air mass ratio calculated for clear sky condition given by Kreith and Kreider [23] as,

$$m = \left[1229 + (614\sin\alpha)^2\right]^{0.5} - 614\sin\alpha \tag{8}$$

Where, α is the sun altitude angle obtained from,

$$\sin\alpha = \cos L \cos\delta \cos h + \sin L \sin\delta \tag{9}$$

L is the latitude angle of the place,

h solar hour angle defined by $h = (12 - t) \times 15^o$ (t is the local time, h), and

δ is the solar declination angle defined by,

$$\delta = 23.5 \sin\left[\frac{360}{365}(J + 284)\right] \tag{10}$$

Where, J is the day number starting from January first.

The hourly global solar radiation intensity on a horizontal surface, R_h can also be obtained from Duffie and Beckman [15] as,

$$R_h = k_t R_a \tag{11}$$

Where, k_t is the daily average clear sky clearness index. The value of k_t can be obtained as a monthly averaged value from NASA website. Table (1) shows the monthly averaged value of k_t in Nile Delta zone from 1995 to 2005. The value of k_t can be obtained as a daily mean value by the MATLAB software through best fitting of the monthly average k_t values over the 365 day of the year.

The sunset hour angle (h_s) is frequently used in solar radiation calculations. The sunset hour angle can be obtained in terms of Latitude and declination angles from Duffie and Beckman [15] as,

$$h_s = \cos^{-1}(-\tan L \tan\delta) \tag{12}$$

An alternative correlation is frequently used to estimate the total solar radiation falling on the horizontal crop surface, namely the Angstrom formula, Hinrichsen [16] as,

$$R_h = \left[a + b\left(\frac{n}{N}\right)\right] R_a \tag{13}$$

Where (a) and (b) are regression constants, expressing the fraction of extraterrestrial solar radiation reaching the earth on overcast days (n = 0) and (n/N) is the ratio of the actual duration of sunshine, n to the maximum possible duration of sunshine or daylight hours N. However, for clear sky (n=N) at sea level, and (a+b=0.75).

Another clear sky model is reported by Hottel [24] for tropical regions, visibility 23 km and altitude less than 2.5 km:

$$R_h = R_a\left[\tau_b \sin(\alpha) + (0.271 - 0.294\,\tau_b)\right] \tag{14}$$

Where, $\tau_b = a_o + a_1 \exp[-k/\sin(\alpha)]$

For the concerned area (few meters above sea levels), a_o=0.122, a_l=0.742 and k=0.395.

The hourly variation of solar radiation is seldom used in estimating the (ET_O) and (ET). The daily global solar radiation is usually used instead. The daily solar radiation on the earth's surface (MJ/m^2day) for these four models can be obtained by integrating equations (6), (11), (13) and (14) over the 24 hours each day of the year. The integration is performed numerically by the MATLAB program. On the other hand, similar data for the same area are collected from NASA website as averaged over 10 years as shown in Table (1).

Referring to equation (1), the daily net radiation R_n (MJ/m^2day) is given by,

$$R_n = R_{ns} - R_{nl} \tag{15}$$

Where, R_{ns} (MJ/m^2day) is the net shortwave radiation resulting from the balance between incoming and reflected solar radiation is given by:

$$R_{ns} = (1 - a')R_h \tag{16}$$

R_{nl} is the net outgoing long wave radiation (MJ/m^2day) expressed quantitatively by the Stefan-Boltzmann law given by Allen et al [10] as,

$$R_{nl} = \sigma\left[\frac{(T_{max}+273)^4 + (T_{min}+273)^4}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{R_h}{R_{hc}} - 0.35\right) \tag{17}$$

Where, (a') is the albedo or canopy reflection coefficient, which is equal to 0.23 for the hypothetical grass reference crop. For clear sky, R_h is equal to that of actual cloudy daily solar radiation (R_{hc}).

Because soil heat flux (G) is small compared to R_n, particularly when the surface is covered by vegetation and calculation time step is 24 hours or longer, the daily soil heat flux is relatively small and may be ignored as reported by Cleugh [25] and thus:

$$G \approx 0 \tag{18}$$

3. RESULTS AND DISCUSSION

The daily mean values of reference evapotranspiration, ET_O (mm/day) are calculated from the Penman-Monteith equation (1). Many terms of this equation depend on the air temperature and also depend mainly on the solar radiation. Equations (3), (4) and (5) are used to calculate the daily mean values of (γ), (e_s) and (Δ) respectively in terms of the daily mean air temperature (T). The actual vapor pressure (e_a) is determined from equation (4) by replacing the mean air temperature by the dew point temperature ($T = T_{dew}$).

Referring to Table (1), the variations of maximum, minimum and monthly average air temperatures obtained from NASA website as average values over 10 years (From 1995 to 2005) are plotted and shown in Fig. 1 along with T_{dew}. The daily mean values can be estimated from the best fit curves derived from the MATLAP computer program. Each best fit function is a fifth degree polynomial and represented by a continuous line as shown in Fig. 1. Referring also to Table (1), the wind speed (U_2) can be taken as an average value of 4.513 m/s over the year.

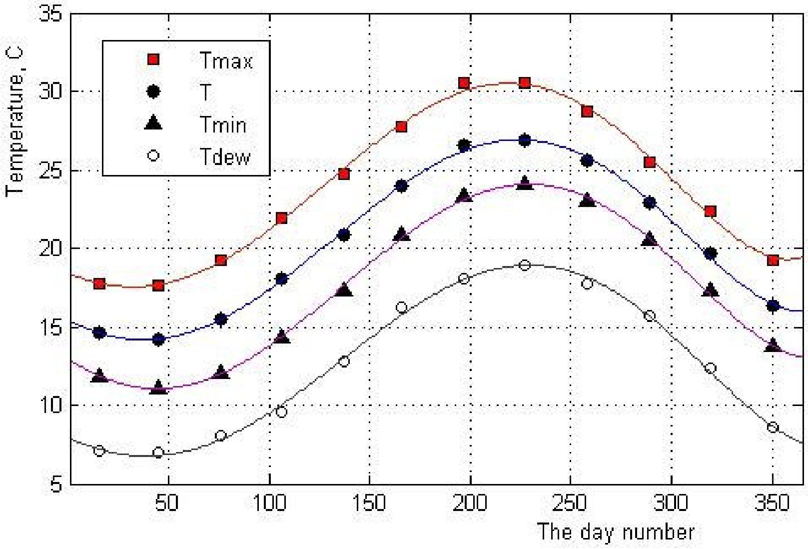

Fig. 1. Variation of T_{max}, T, T_{min} and T_{dew} at the Nile Delta of Egypt. (L=31° N).

Figures 2, 3 and 4 show the hourly total solar radiation on a horizontal surface (W/m^2) in three days representing the winter, equinoxes and summer seasons respectively. These figures show also the solar radiation as calculated from four models by equations (6), (11), (13) and (14). The calculations are carried out with a time step of 0.01 hour for better accuracy. It is clear that there is a considerable difference between results of different models increases from zero to a maximum value at noon for a given day. The difference increases from a minimum value of 40 W/m^2 at summer to a maximum value of 60 W/m^2 at winter solstice.

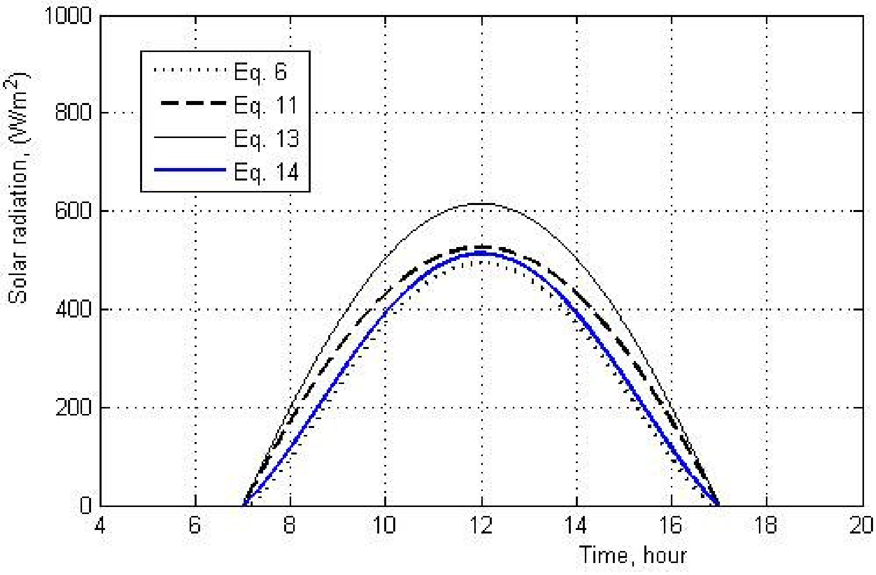

Fig. 2. Hourly solar radiation on a horizontal surface at December, 21 (L=31° N).

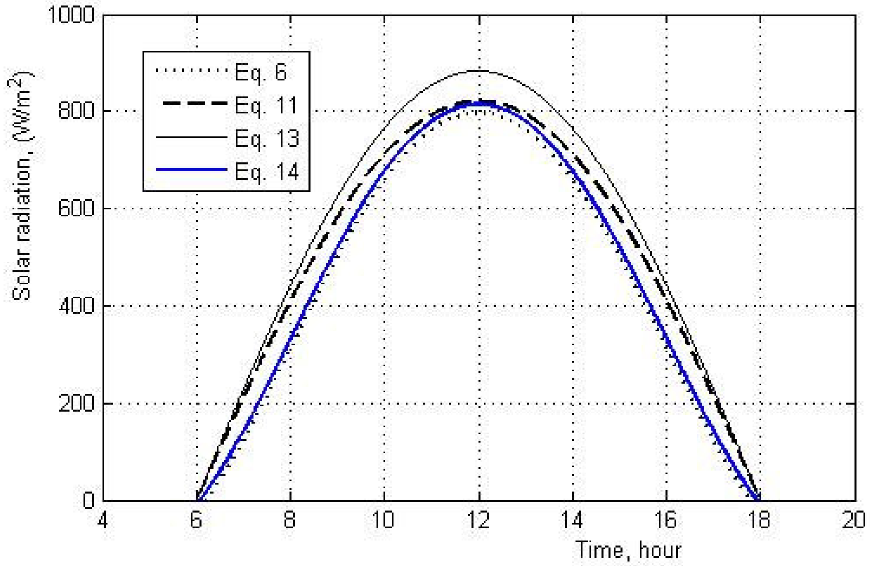

Fig. 3. Hourly solar radiation on a horizontal surface at March/Sept., 21 (L=31° N).

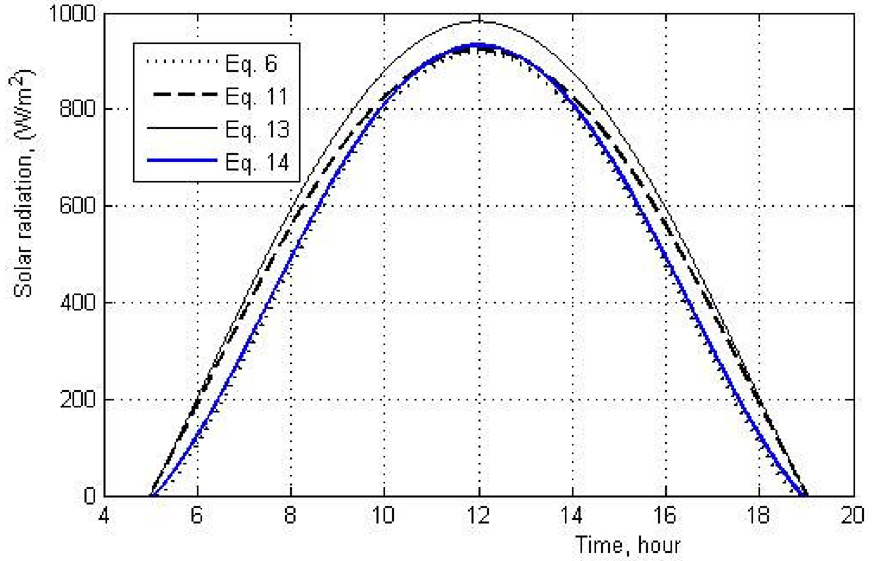

Fig. 4. Hourly solar radiation on a horizontal surface at June, 21 (L=31° N).

Equations (6), (11), (13) and (14) are integrated numerically by the MATLAB software to calculate the total daily solar radiation in any day of the year. Figure 5 shows the daily total solar radiation on a horizontal surface (MJ/m^{2}day) at the concerned area for these four models. The difference between models results is pronounced and reached about 5 MJ/m^{2}day. The data collected from NASA averaged over 10 years are also plotted for models verification and comparison. It is clear that the clear sky model by Hottel [24] using equation (14) shows the closest results to that obtained from NASA website.

Results show also that the total daily solar radiation obtained by Hinrichsen [16] using equation (13) is the highest compared to the other ones.

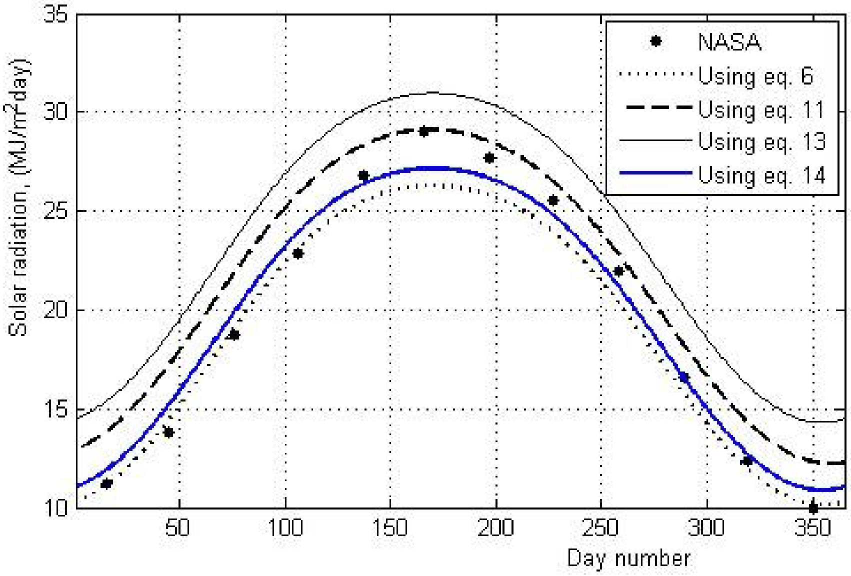

Fig. 5. Solar radiation on earth's surface at (Latitude 31^o N and longitude 31^o E).

Substituting the results in equations (15), (16) and (17), the daily values of net solar radiation (R_n, MJ/m^{2}day) can be calculated all over the year. Then, using above results in the Penman-Monteith equation (1), the reference evapotranspiration (ET_O, mm/day) can be calculated for the 365 days of the year. Results obtained from the four models estimating the solar radiation are shown in Fig. 6. The difference between results ranges from 2.47-3 mm/day in winter to 6.46-7.257 mm/day in summer solstice.

It is quite useful to sense the effect of this maximum difference in solar radiation on the change in reference evapotranspiration ET_O (mm/day). Figure 7 shows that a solar radiation difference of 4.19–4.63 (MJ/m^{2}day) yields a change in the ET_O of 0.521-0.793 (mm/day) The maximum difference in solar radiation is that obtained by subtracting the results of equation (6) from that obtained from equation (13). The same is considered in the maximum difference of ET_O as show in Figs. 6 and 7.

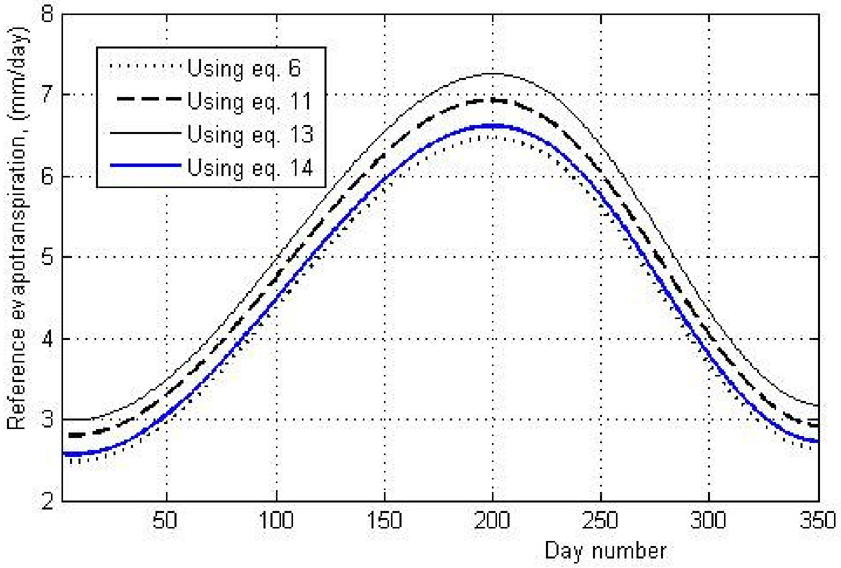

Fig. 6. Variation of ET_o all over the year (Latitude 31^o N and longitude 31^o).

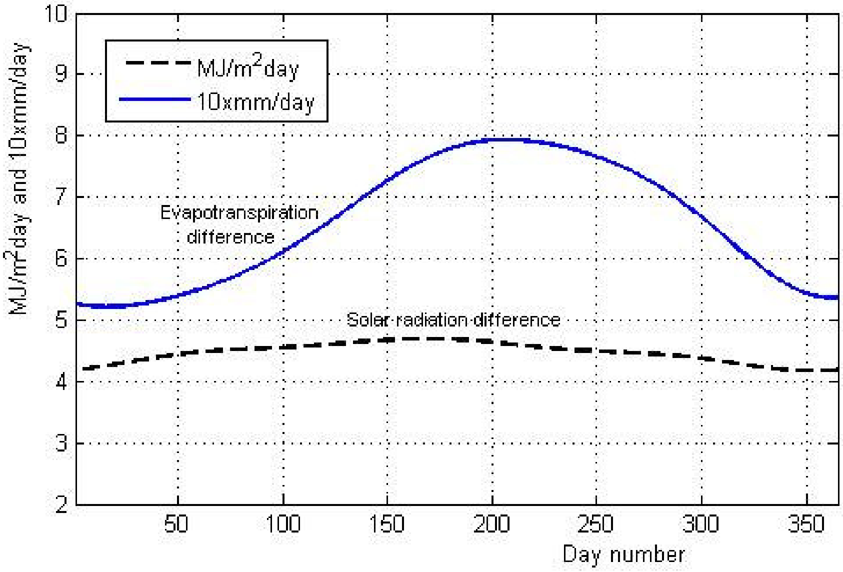

Fig. 7. Effect of difference in daily solar radiation on the change in ET_O.

4. CONCLUSIONS

The proper estimation of crops water needs is essential for water saving. The Penman-Monteith equation is frequently used for calculating the reference evapotranspiration ET_O and hence the crop water requirements ET. This equation depends mainly on the solar radiation. In this work, the effect of solar radiation on the ET_O is investigated. For this reason, a MATLAB software is constructed and used for computation of ET_O at the daily solar radiation on the river Nile Delta of Egypt. Comparison of results obtained from alternative formulae used to calculate solar radiation is carried out and compared to that obtained from NASA. Results are shown in graphical form, and can be concluded as follows:

1. More accurate results, equations (3), (4) and (5) are used to calculate the daily mean values of (γ), (e_s) and (Δ) respectively in terms of the daily mean air temperature (T). The actual vapor pressure (e_a) is determined from equation (4) at the dew point temperature, with the wind speed (U_2) can be taken as an average value of 4.513 m/s over the year. Since the results from these equations fit exactly with that based on the relationship correlated by Allen et al [10].

2. The maximum, minimum and monthly average air temperatures obtained from NASA website as average values over 10 years are used in calculation of ET_O. The daily mean values can be estimated from the monthly average best fit curves derived from the MATLAP computer program. Each best fit function is a fifth degree polynomial and represented graphically.

3. Equations (6), (11), (13) and (14) are integrated numerically by the MATLAB software to calculate the total daily solar radiation in any day of the year with a time step of 0.1 hour.

4. The difference between results of different models, Equations (6), (11), (13) and (14), in three days representing the winter, equinoxes and summer seasons

respectively, increases from zero to a maximum value at noon for a given day. The difference increases from a minimum value of 40 W/m^2 at summer to a maximum value of 60 W/m^2 at winter solstice.

5. The difference of the total daily solar radiation at the concerned area between different models results is pronounced and reached about 5 MJ/m^2day.
6. The clear sky model by Hottel [24] using equation (14) shows the closest results to that obtained from NASA website.
7. The total daily solar radiation obtained by Hinrichsen [16] using equation (13) shows the highest results compared to the other ones.
8. The reference evapotranspiration ET_O, mm/day is calculated for the 365 days of the year. Results of ET_O range from 2.47 - 3 mm/day in winter to 6.46 - 7.257 mm/day in summer solstice.
9. The total daily solar radiation maximum difference of 4.19 – 4.63 (MJ/m^2day) yields a change in the ET_O of 0.521 - 0.793 (mm/day).
10. The maximum difference in solar radiation is that obtained by subtracting the value of equation (6) from that obtained from equation (13). The same is considered in the maximum difference of ET_O.

Finally, these results represent an accurate and quick tool for estimation of the reference evapotranspiration (ET_O) and water requirements (ET) of different crops in the Nile Delta zone of Egypt.

5. NOMENCLATURE

a, b	Regression constants,
a’	The albedo or canopy reflection coefficient,
C_p	Specific heat of air at constant pressure = 1.005 (kJ/kg ºC),
e_a	Actual air vapor pressure (kPa),
e_s	Saturation air vapor pressure (kPa),
ET	Crop evapotranspiration under standard conditions (mm/day),
ET_O	Reference crop evapotranspiration (mm/day),
h	Solar hour angle (rad),
h_s	Sunset hour angle (rad),
G	The soil heat flux density (MJ/m^2 day),
J	The day number starting from January first,
k_C	Crop coefficient,
k_t	Monthly averaged clear sky clearness index,
L	Latitude angle of the place (deg, rad),
m	Air mass ratio,
(n/N)	The ratio of the actual duration of sunshine,
P	The atmospheric pressure=101.3 (kPa),
R_a	Extraterrestrial solar radiation on a horizontal surface (W/m^2) or ($MJ/m^2.day$),
R_h	Solar radiation on a horizontal surface (clear sky) (W/m^2) or ($MJ/m^2.day$),
R_{hc}	Solar radiation on a horizontal surface (actual cloudy) (W/m^2) or ($MJ/m^2.day$),
R_n	Net solar radiation at the crop surface (W/m^2) or ($MJ/m^2.day$),

R_{nl}	Net outgoing long wave radiation (W/m^2) or ($MJ/m^2.day$),
R_{ns}	Net short wave radiation resulting from the balance between incoming and reflected solar radiation (W/m^2) or ($MJ/m^2.day$),
t	The local time (h),
T	The mean daily air temperature (°C),
T_{dew}	The dew point temperature (°C),
T_{max}	The maximum air temperature (°C),
T_{min}	The minimum air temperature (°C),
U_2	Wind speed (m/s),

Greek symbols

α	Sun altitude angle
δ	Solar declination angle
Δ	Slope of vapor pressure curve (kPa/°C)
γ	Psychrometric constant (kPa/°C)
λ	Latent heat of vaporization (MJ/kg)
ε	Ratio between molecular weight of water vapor/dry air = 0.622
τ_b	The atmospheric transmittance coefficient
σ	The Stefan-Boltzmann constant ($4.903\ 10^{-9}$ MJ/ K^4m^2day).

REFERENCES

[1] FAO, Bruinsma, J., “World agriculture: towards 2015/2030”, A FAO Perspective. Earthscan Publications Ltd., London, 2003.

[2] Ismail, S.M., "Design and management of field irrigation systems", pp. 5-188 Elmarefa, Alex, 2002.

[3] Hongjie X., Jan H., Shirley K. and Eric S., “Comparison of evapotranspiration estimates from the surface energy balance algorithm (SEBAL) and flux tower data; middle Rio Grande Basin”, Evapotranspiration Available, http://www.nmt.edu, November, 2002.

[4] Kalluri S., Gilruth P., Bergman P. and Plante R., “Impacts of NASA’s remote sensing data on policy and decision making at state and local agencies in the United States”, Evapotranspiration Available http://earthoutlook.east.hitc.com, August, 2003.

[5] Islam A.E.M., “Real-time crop coefficient from SEBAL method for estimating the evapotranspiration, remote sensing for agriculture, ecosystems, and hydrology”, Proceedings of the SPIE, Vol. 5232, 100-9, 2004.

[6] Penman H.L., “Natural evaporation from open water, bare soil and grass”, Proceedings of the Royal Society of London, A193: 120-46, 1948.

[7] Monteith J.L., “Evaporation and the environment in the state and movement of water in living organisms”, 19th Symposia of the Society for Experimental Biology. Cambridge University Press, London, U.K. p. 205-34, 1965.

[8] Priestley C.H.B. and Taylor R.J., “On the assessment of surface heat flux and evaporation using large-scale parameters”, Mon. Weather Rev 100, 81-92, 1972.

[9] Hargreaves G.H. and Samani Z.A., “Reference crop evapotranspiration from temperature”, Applied Engineering in Agriculture 1, 96-9, 1985.

[10] Allen, R.G., Pereira, L.S., Raes, D., and Smith, M., “Crop evapotranspiration; guidelines for computing crop requirements”, Food and Agriculture Organization (FAO), Irrigation and drainage paper 56. Rome, Italy, 1998.

[11] Droogers, P. and Allen, R.G., “Estimating reference evapotranspiration under inaccurate data conditions”, Irrigation and Drainage Systems, 16(1): 33-45, 2002.

[12] Popova, Z., Kercheva, M. and Pereira, L.S., “Validation of the FAO methodology for computing ET0 with limited data”, ICID 21st European Regional Conference, Frankfurt and Slubice, 13 pp, 2006.

[13] Llasat, M.C. and Snyder, R.L., “Data error effects on net radiation and evapotranspiration estimation”, Agricultural and Forest Meteorology, 91(3/4): 209-221, 1998.

[14] Meinel, A. and Mainel, M., “Applied solar energy; an introduction”, Addison-Wesley, Reading, MA, 1976.

[15] Duffie J.A. and Beckman, W.A., “Solar engineering of thermal processes”, John Wiley and Sons Inc, New York, 1991.

[16] Hinrichsen, K., “The Angstrom formula with coefficients having a physical meaning”, Solar Energy, Vol. 52. No.6, 1994.

[17] Gong L., Chong-yu Xu, Deliang Chen, Sven Halldin and Yongqin David Chen, “Sensitivity of the Penman–Monteith reference evapotranspiration to key climatic variables in the Changjiang (Yangtze River) basin”, Journal of Hydrology, 329, 620-629, 2006.

[18] Bois B., P. Pieri, C. Van Leeuwen, L. Wald, F. Huard, J.P. Gaudillere and E. Saur, “Using remotely sensed solar radiation data for reference evapotranspiration estimation at a daily time step”, Agricultural and Forest Meteorology 148, 619-630, 2008.

[19] http://eosweb.larc.nasa.gov/cgi-bin/sse/interann.cgi.

[20] Harrison, L. P., “Fundamental’s concepts and definitions relating to humidity”, In Wexler, A (Editor) Humidity and moisture, Vol. 3, Reinhold Publishing Co., New York, 1963.

[21] Murray, F. W., “On the computation of saturation vapor pressure”, J. Appl. Meteor. 6: 203-204, 1967.

[22] Markvart, T. and Kreider, Ed., “Solar electricity”, John Wiley & Sons, Chichester, U.K, 1994.

[23] Kreith, F. and Kreider, J.F., “Principles of solar engineering”, McGraw-Hill, New York, 1994.

[24] Hottel. H.C., "A simple model for estimating the transmittance of direct solar radiation through clear atmospheres”, Solar Energy, 18, 129, 1976.

[25] Cleugh, H.A., R. Leuning, Q.Z. Mu, and S.W. Running, “Regional evaporation estimates from flux tower and MODIS satellite data”, Remote Sensing of Environment, 106, 285-304, 2007.