PERFORMANCE OF VAPOUR PRESSURE MODELS IN THE COMPUTATION OF VAPOUR PRESSURE AND EVAPOTRANSPIRATION IN ABHA, ASIR REGION, SAUDI ARABIA

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Abstract. The FAO-56 Penman-Monteith model is recognized as the standard method for estimating reference evapotranspiration (ETo) which requires daily meteorological data as inputs. Among all input data, vapour pressure deficit (VPD) is one of the critical parameter that drives evapotranspiration (ETo), and is of fundamental importance in crop models. In this study effort has been made to compare six vapour pressure models during four seasons. Three vapour pressure models (Models 1–3) selected as mentioned in Irrigation and Drainage Paper-56 of the Food and Agriculture Organization (FAO-56) and Models 4-6 has been selected from literature survey. Model 1, which uses daily maximum and minimum temperature, relative humidity (RH), is the preferred method to estimate actual air pressure (AE) hence it is used as standard for comparing other models. The effectiveness of vapour pressure models were measured by statistical tools and ranked according to Global Performance Indicator (GPI) where higher value of GPI represent best model. The ranking order using GPI shows that Model 5 resulted in best estimation capability with a GPI of 2.77. Moreover, the effect of variation in wind speed on the performance of the vapour pressure models in ETo estimation is also assessed.
Keywords: *agriculture, cropping period, global performance index, vapour pressure deficit, water deficit*

Introduction

The Kingdom of Saudi Arabia (KSA) like Semi-Arid Asir region Abha suffers large water deficit which is due to climate change during past decades. Climate change is crucial part for well-planned water resource management in semi-arid region, Saudi Arabia (Tarawneh and Chowdhury, 2018). Therefore, it is important to understand relation of climatic parameter with environment in order to reduce vulnerability caused by growing new crops in climate change environment and for efficient water management system (DeNicola et al., 2015). Earlier studies have stated an increase of agricultural water demand by 5–15% during 2050, due to increased evapotranspiration rate. According to Chowdhury and Al-Zahrani (2013), rise of temperature by 1 °C would

likely to change the thermal limits of a crop by 10–30%, which will affect crop yields (Lelieveld, 2012). Apart from this, rise in temperature by 1 °C would likely to increase the capacity of air to hold water vapour by 7%, which in turn reduces precipitation rate (Trenberth, 2011). Hence, the water resources system and soil–water balance system will affect further (Kang et al., 2009).

The water consumption by agricultural field is estimated to be 88% of the annual water use (Multsch et al., 2017). The water shortage in Saudi Arabia indicates highest index as compared to other countries (Baig and Straquadine, 2014). Al-Zahrani (2019) stated that the KSA is portrayed among few countries where withdrawal of water exceeds 33.33% of the total available water supply. The irrigation of agricultural field requires knowledge of when to irrigate and the amount of water to apply. This depends on local atmospheric conditions, where precipitation and evapotranspiration (ETo) play a key role (Kumar et al., 2012). Hence knowledge of ETo is essential in water resources management, for both natural and agricultural ecosystems, particularly for irrigation (Allen et al., 1998).

The Direct method of estimating evapotranspiration is lysimeter which provides high accuracy (Liu et al., 2017; Hirschi et al., 2017). However, it is very costly and requires many highly expensive and sophisticated equipment for measurement. To overcome this problem the frequently used method for obtaining reference evapotranspiration presented in the Food and Agricultural Organization of the United Nations (FAO) Irrigation and Drainage Paper 56 depends only on meteorological observations and crop coefficients estimated based on surface conditions (Allen et al., 1998). The application of FAO56-PM is limited due to an insufficient network of the meteorological observatory and proper maintenance (Pandey et al., 2016). Alternatively, numerous studies in different climatic conditions evaluated the applicability of less data-demanding empirical ETo methods using sophisticated and straightforward techniques against FAO56- PM (Pandey and Pandey, 2018; Cadro et al., 2017). However, the FAO-56 Penman–Monteith Model which bears high correlation with lysimeter measurement for estimated of evapotranspiration (Nolz et al., 2016). The reference crop evapotranspiration (ETo) estimations using the FAO Penman-Monteith equation (PM-ETo) require a set of weather data including maximum and minimum air temperatures (Tmax, Tmin), actual vapour pressure, solar radiation, and wind speed. Among all weather parameter, vapour pressure deficit is an important factor in the estimation of ETo. It is defined as difference between saturated vapour pressure and actual vapour pressure (Seager et al., 2015). Various models are available to estimate vapour pressure. However, use of different models in determining actual vapour pressure will result in different values of actual vapour pressure and thus different values of ETo will be estimated. In some earlier studies (Burman et al., 1987; Weiss, 1977), it was observed that ETo can be determined with good accuracy regardless of the model used for the vapour pressure estimation. However, a few studies (Saxton, 1975; Sadler and Evans, 1989; Yoder et al., 2005), which were carried out to analyse the sensitivity of ETo to the vapour pressure deficit (VPD), suggested a considerable change in estimated ETo values when the value of VPD changed. Howell (1995) evaluated some methods that calculate VPD for Bushland (Texas). Weather data containing maximum-minimum temperature along with mean dewpoint temperature were found to provide the most accurate calculations of VPD in the study area. Ojha et al. (2010) compared the performance of the three FAO-56 models (for ea estimation) in the estimation of open water evapouration in a semiarid region (Udaipur, India). Their results showed that Model 1 performed better than the other two models in estimating open water evapouration using the Penman combination approach.

The past studies in the study region were basically on assessing different ETo models against theFAO-56 Penman Monteith model based on Central and Eastern region of Saudi Arabia (Salih and Sendil, 1984; Al-Omran et al., 2004; Elnesr et al., 2010; Al-Ghobari, 2000; Madugundu et al., 2017). However, no such studies recorded so far about the vapour pressure model from the literature in Kingdom of Saudi Arabia. In order to fill this void, an effort was made to estimate six vapour pressure model based on availability of meteorological data for the period from 1988-2018 and by recognizing the best suitable method by computing global performance index as an alternative to model 1 which is taken as standard in this study. The finding of the research work can be helpful in reducing the error during evapotranspiration computation, Moreover the best evaluated model equation for evapotranspiration could assist in computing evapotranspiration in future in the field of crop water management system, climate change studies, irrigation and water resource planning.

Study area

Site description

The research work deals with Abha mountainous region of Asir province, Kingdom of Saudi Arabia having an area of 370 km^2 located between the latitude of 18°10′12.39″N and 18°23′33.05″N and longitude of 42°21′41.58″E and 42°39′36.09″E as shown in *Figure 1*. The zone is prone to heavy rainfall as compared to other parts of Saudi Arabia. The elevation varies from 1951 to 2991 m (msl) with average precipitation of 355 mm which mainly occurs between June and October. According to the topographical features of the investigation region, it is found to have weak geology because of the precipitation and slope nature during the past few years (Mallick et al., 2018).
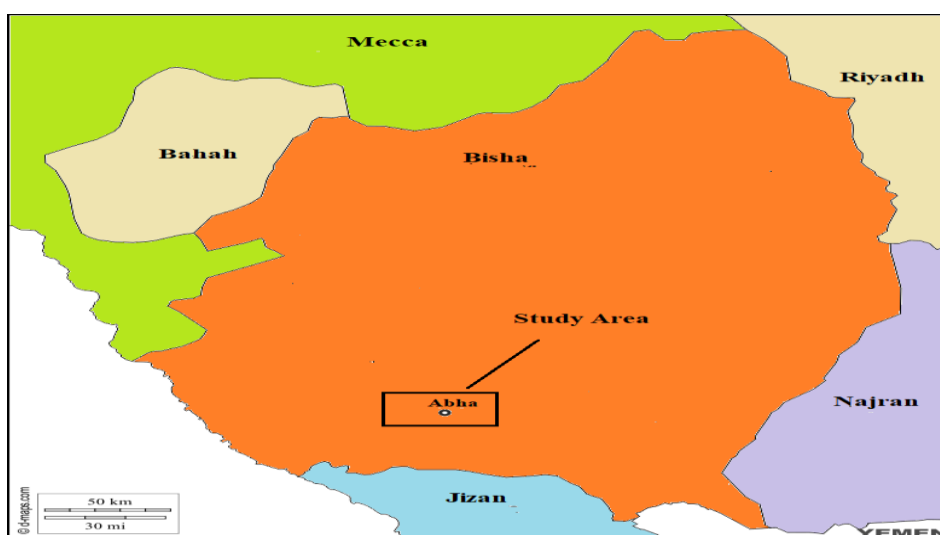

Figure 1. Location map of Abha Asir region, Kingdom of Saudi Arabia

Data availability

In this research work, weather parameters were collected from Abha meteorological weather station for the period between 1988–2018 which includes wind velocity, maximum and minimum temperature, mean temperature, mean relative humidity and

solar radiation as well. The data collected were checked by (Allen, 1996). The variation of minimum, maximum and mean temperature along with standard deviation is shown in *Figure 2a-c,* while the mean, minimum and maximum relative humidity along with standard deviation is shown in *Figure 2d-f.*
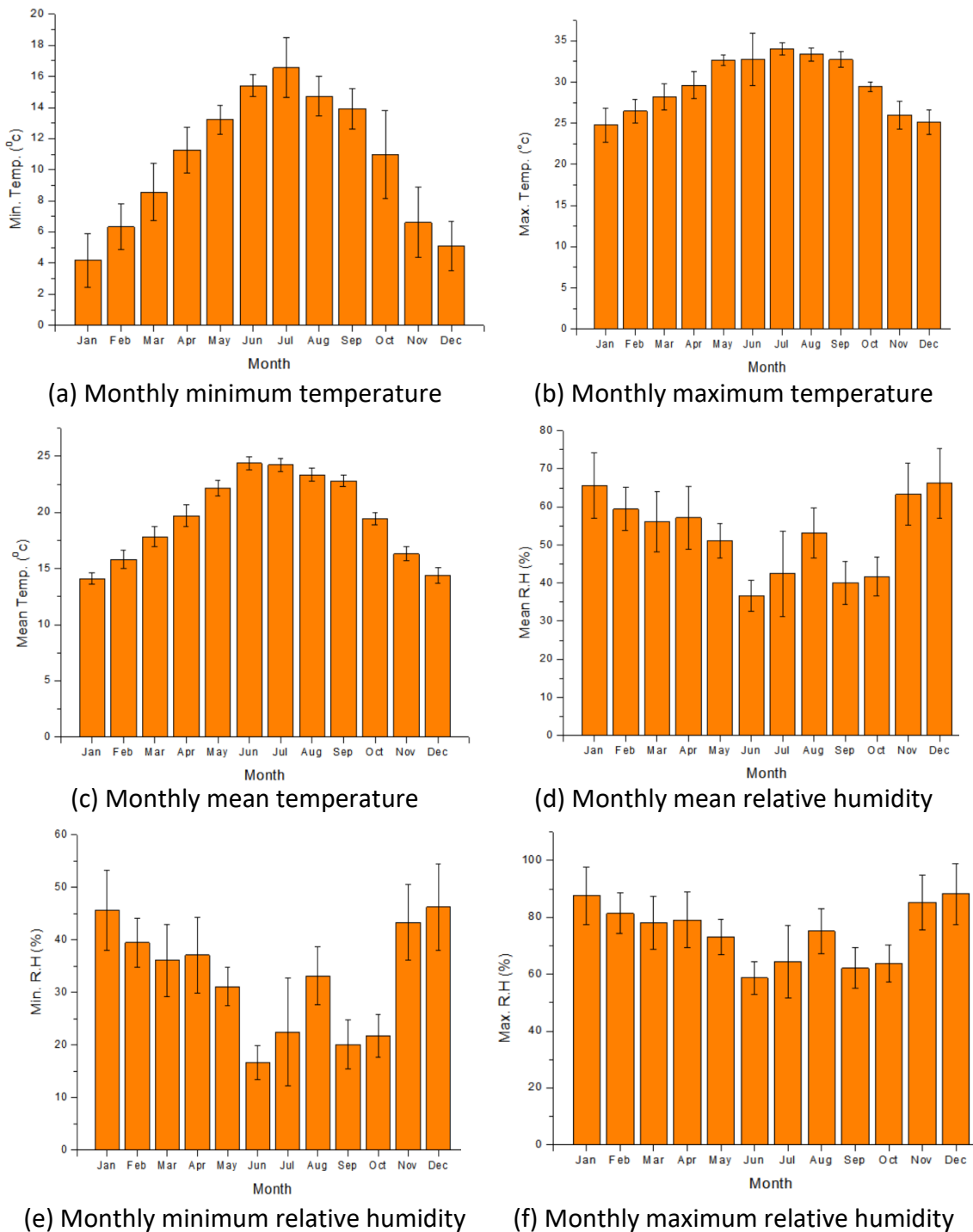

(a) Monthly minimum temperature

(b) Monthly maximum temperature

(c) Monthly mean temperature

(d) Monthly mean relative humidity

(e) Monthly minimum relative humidity

(f) Monthly maximum relative humidity

Figure 2. *Average monthly climatic data value for the period between 1988 and 2018*

Methodology

Various vapour pressure model taking into account in this study are based on available literature. In this research work vapour pressure model were estimated by six model based on available climatic data. The values estimated from different model were compared with the value obtained from standard model 1 for four seasons as shown in *Table 1*, where each of the four cropping seasons is divided into four crop growth stages as per the guidelines provided in Allen et al. (1998). The four crop growth stages are (I) initial stage, (II) development stage, (III) midseason stage, and (IV) end season stage. The crop growth stages are used as periods to compare the actual vapour pressure and ETo values determined by using the six VP models. The performance of vapour pressure models was computed based on overall effect of evaluation criteria called as Global performance index. The ranking was done in order to get most promising model which can be used alternative to model 1. The flowchart as shown in *Figure 3* described the stepwise procedure to compute most promising model among five model (excluding model 1) to be used as alternate of model 1.

Table 1. *Details of the cropping periods*

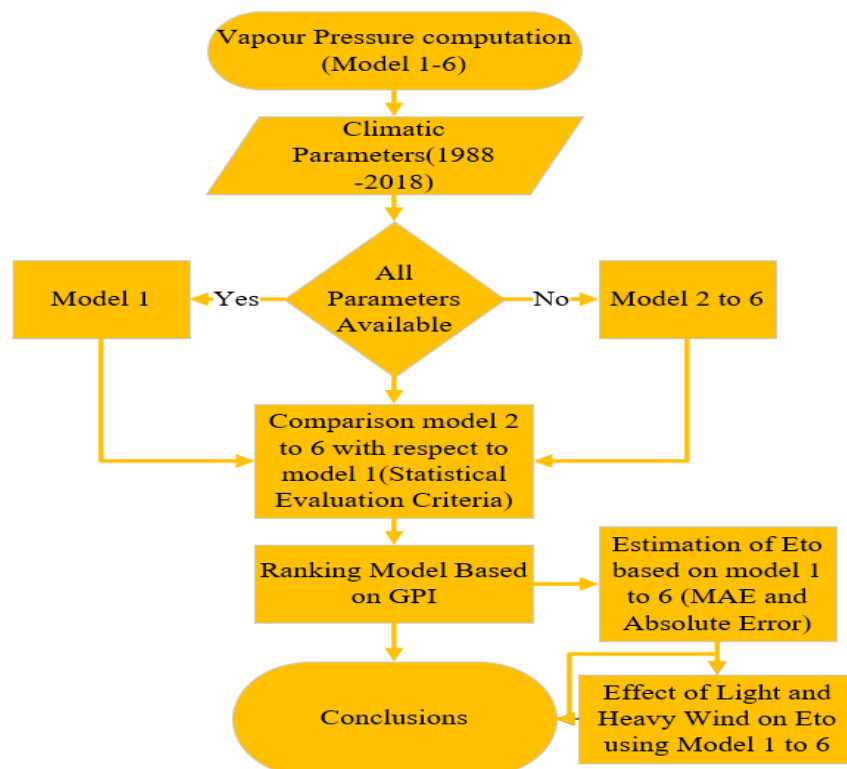| Season	Duration		Crop growing stage				Total days
	From	**To**	**I**	**II**	**III**	**IV**	
Winter	21-Dec	20-Mar	10	20	40	20	90
Spring	21-Mar	20-Jun	10	20	40	22	92
Summer	21-Jun	22-Sep	10	20	40	23	93
Autumn	23-Sep	20-Dec	10	20	40	20	90

Figure 3. *Flowchart for methodology*

Reference evapotranspiration and vapour pressure model

This study work aims to analyse various vapour pressure models which is one of the most critical component of reference evapotranspiration computation by the standard FAO56-PM model in the Abha Asir region, Kingdom of Saudi Arabia. The selection of methods was based on their wide acceptance, simple calculation procedure and applicability in present conditions. The models are shown by *Equations 2-8*. If all the required variables are available, it is advisable to use Model 1. Model 2 is used when the credibility of minimum RH (RHmin) data is in doubt, whereas Model 3 is used when only mean RH (RHmean) data are available. Details about the calculation of actual vapour pressure using RH and temperature data can also be found in Allen et al. (2011). The use of different models in determining actual vapour pressure will result in different values of actual vapour pressure and thus different values of ETo will be estimated.

The FAO Penman-Monteith equation for estimating ETo values recommended by Food and Agriculture Organisation, Irrigation and Drainage Paper-56 (FAO-56) (and is given as *Eq. 1*) and moreover equation for vapour pressure (Models 1-3) also suggested in FAO-56 documentation (Allen et al., 1998):

$$ETo = \frac{0.408 \times \Delta \times (Rn-G) + \gamma \times \left(\frac{900}{T+273}\right) \times u_2 \times (e_s - e_a)}{\Delta + \gamma \times (1+0.34u_2)} \tag{Eq.1}$$

$$\text{Model 1} \quad e_a = \frac{\left[\left\{e_s(T_{min}) \times \frac{RH_{max}}{100}\right\} + \left\{e_s(T_{max}) \times \frac{RH_{min}}{100}\right\}\right]}{2} \tag{Eq.2}$$

$$\text{Model 2} \quad e_a = e_s(T_{min}) \times \frac{RH_{max}}{100} \tag{Eq.3}$$

$$\text{Model 3} \quad e_a = \frac{RH_{mean}}{100} \times \left[\frac{\{e_s(T_{max}) + e_s(T_{min})\}}{2}\right] \tag{Eq.4}$$

A VP model (referred here as Model 4), which uses RHmean and Tmean for calculation of actual vapour pressure was reported by Irmak et al. (2005) represented by *Equation 5:*

$$\text{Model 4} \quad e_a = \frac{RH_{mean} \times e_s(T_{mean})}{100} \tag{Eq.5}$$

Upreti and Ojha (2017) suggested that by using the Lawrence Tdew–RH relationship (*Eq. 6*), fairly accurate estimates of dewpoint temperature can be obtained, which in turn can be used for the calculation of actual vapour pressure values:

$$T_{dew} \perp = T_{mean} - (20 - 0.2 RH_{mean})\left(\frac{T_{K-mean}}{300}\right)^2 - 0.00135(RH_{mean} - 84)^2 + 0.35 \tag{Eq.6}$$

where Tdew ⊥ = dew point temperature value in °C obtained using the Tdew–RH relationship proposed by Lawrence (2005); Tmean (°C) and RHmean (%) are the daily mean values of temperature and RH, respectively; TK mean is the daily mean temperature in kelvin.

Values of Tdew ⊥ (determined by using *Equation 6*) are then used to calculate the daily actual vapour pressure values using *Equation 7*. This proposed approach is mentioned here as Model 5:

$$\text{Model 5} \quad e_a(T) = 0.6108 exp\left[\frac{17.27 T_{dew} \perp}{T_{dew\perp} + 237.3}\right] \tag{Eq.7}$$

As per FAO-56 document (Allen et al., 1998), daily values of actual vapour pressure can be estimated by using *Equation 8* assuming daily minimum temperature (Tmin) near the dewpoint temperature (T_{dew}):

$$\text{Model 6} \quad e_a(T) = 0.6108 exp\left[\frac{17.27 T_{min}}{T_{min} + 237.3}\right] \tag{Eq.8}$$

$$e_s = 0.6108 exp\left[\frac{17.27 T_{mean}}{T_{mean} + 237.3}\right] \tag{Eq.9}$$

$$e_s = \frac{\{e_s(T_{max}) + e_s(T_{min})\}}{2} \tag{Eq.10}$$

Note: ETo = reference evapotranspiration (mm day−1); Rn = net radiation at the crop surface (MJm^{-2} day^{-1}); G = soil heat flux density (MJm^{-2} day^{-1})) that is taken as zero for daily ETo estimation; T = temperature at 2 m height (°C); u2 = wind speed at 2 m height (m s^{-1}); es = saturation vapour pressure (kPa); ea = actual vapour pressure (kPa); (es–ea) = vapour pressure deficit (kPa); Δ = slope of vapour pressure curve (kPa °C^{-1}); and γ = psychrometric constant (kPa °C^{-1}); T_{max} = Maximum Temperature (°C); T_{min} = Minimum Temperature (°C); T_{mean} = Mean Temperature (°C); RH_{mean} = Mean Relative Humidity (%); RH_{max} = Maximum Relative Humidity (%); RH_{min} = Minimum Relative Humidity (%); T_{dew} ⊥=dew point temperature value in °C; $T_{K\,-mean}$ is the daily mean temperature in kelvin.

Evaluation criteria and global performance index (GPI)

The GPI is computed by using ten statistical measure such as Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Mean Absolute Relative Error (MARE), Uncertainty at 95% (U95), Root mean squared relative error (RMSRE), Relative Root Mean Square Error (RRMSE), Mean Bias Error (MBE), Coefficient of determination (R^2), Maximum Absolute Relative Error (erMax) and t-statistics (Ali and Jamil, 2019). For Coefficient of determination (R^2), 1 is taken as ideal value, while for all other statistical zero is taken as ideal value. Despotovic et al. (2015) proposed the GPI by scaling the values of statistical tools in between 0 and 1. Further by subtracting the scaled values of error indicators from the corresponding medians and adding up the differences so obtained using the weight factors. Mathematically, for the ith model:

$$GPI_i = \sum_{j=1}^{10} \alpha_j \left(\tilde{y}_j - \tilde{y}_{ij}\right) \tag{Eq.11}$$

where α_j have a value of + 1 for statistical errors having a recommended value of 0 and a value of -1 for statistical errors that have a recommended high value of 1 (e.g. R^2). $\tilde{y}_j$ and $\tilde{y}_{ij}$ are the median and scaled values, respectively.

Willmott and Matsuura (2005) used MAE as statistical measure as shown by *Equation 12*:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|e_{a,Mi} - e_{a,M1}| \tag{Eq.12}$$

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(e_{a,Mi} - e_{a,M1})^2\right]^{\frac{1}{2}} \tag{Eq.13}$$

$$MARE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{e_{a,Mi} - e_{a,M1}}{e_{a,Mi}}\right| \tag{Eq.14}$$

Behar et al. (2015) and Gueymard (2014) applied U_{95} in modelling of solar radiation as given by *Equation 15:*

$$U_{95} = 1.96(SD^2 + RMSE^2)^{\frac{1}{2}} \tag{Eq.15}$$

$$RMSRE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{e_{a,Mi} - e_{a,M1}}{e_{a,Mi}}\right)^2} \tag{Eq.16}$$

Li et al. (2013) applied RRMSE as a statistical performance measure in the modelling of global solar radiation as given by *Equation 17:*

$$RRMSE = 100 \times \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(e_{a,Mi} - e_{a,M1})^2}}{\sum_{i=1}^{n}e_{a,Mi}} \tag{Eq.17}$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(e_{a,Mi} - e_{a,M1}) \tag{Eq.18}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(e_{a,Mi} - e_{a,M1})^2}{\sum_{i=1}^{n}\left(e_{a,Mi} - e_{a,Mi_{av}}\right)^2} \tag{Eq.19}$$

$$erMAX = max\left(\left|\frac{e_{a,Mi} - e_{a,M1}}{e_{a,Mi}}\right|\right) \tag{Eq.20}$$

$$t = \left[\frac{(n-1)MBE^2}{RMSE^2 - MBE^2}\right]^{\frac{1}{2}} \tag{Eq.21}$$

Results

Comparison of the actual vapour pressure values

In this study work six vapour pressure models are used for the computation of daily actual vapour pressure values which is one of the important parameter for estimating

daily ETo values. *Table 2* shows the average of daily values of actual vapour pressure for the crop growth stages of the four seasons (winter, spring, summer, autumn). Each of the four cropping seasons is divided into four crop growth stages as per the guidelines provided in Allen et al. (1998). The four crop growth stages are (I) initial stage, (II) development stage, (III) midseason stage, and (IV) end season stage. The crop growth stages are used as periods to compare the actual vapour pressure and ETo values determined by using the six VP models.

**Table 2.** *Average of daily ea(kPa) for the crop growth stages of the four seasons*

Stages	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Winter						
Initial	1.07	1.00	1.33	1.09	1.04	1.25
Development	1.06	0.95	1.21	1.09	1.04	1.22
Mid season	1.07	0.97	1.19	1.10	1.05	1.25
Late season	1.17	1.07	1.27	1.20	1.14	1.32
Overall	1.09	1.00	1.25	1.12	1.07	1.26
Spring						
Initial	1.11	1.02	1.24	1.15	1.09	1.25
Development	1.22	1.12	1.37	1.26	1.19	1.40
Mid season	1.26	1.16	1.41	1.29	1.24	1.45
Late season	1.09	1.01	1.16	1.12	1.11	1.32
Overall	1.17	1.08	1.30	1.20	1.16	1.35
Summer						
Initial	1.08	1.00	1.15	1.11	1.11	1.32
Development	1.24	1.15	1.38	1.28	1.23	1.44
Mid season	1.38	1.28	1.55	1.41	1.36	1.57
Late season	0.99	0.92	1.04	1.01	1.00	1.21
Overall	1.17	1.09	1.28	1.20	1.18	1.39
Autumn						
Initial	1.09	1.02	1.18	1.12	1.10	1.31
Development	0.88	0.83	0.96	0.90	0.87	1.08
Mid season	1.05	0.98	1.14	1.07	1.02	1.23
Late season	1.05	0.98	1.14	1.07	1.02	1.23
Overall	1.02	0.95	1.11	1.04	1.00	1.21

The estimated actual vapour pressure values depends on the air temperature and amount of humidity in the air. The daily values of actual vapour pressure calculated using the six VP models is shown in *Figure 4*. Among six VP models, Model 1 which uses daily maximum and minimum values of temperature and RH, is considered the most reliable model for determining the values of actual vapour pressure and is recommended if all the meteorological variables required are available.

Models 2 and 3 should be used only if any of the data required for Model 1 are either unavailable or doubtful (Allen et al.,1998; Ojha et al., 2010). Therefore, the daily values of actual vapour pressure calculated using Models 2–6 are compared with the daily values of actual vapour pressure obtained by using Model 1 in order to find which VP model should be used if all meteorological variables required for Model 1 are not available. The daily percentage errors of Models 2–6 averaged for 12-day intervals in the determination of actual vapour pressure values are shown in *Figure 5*.
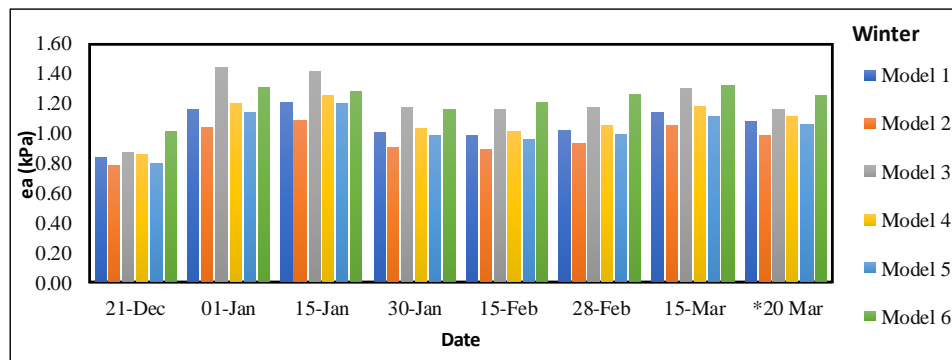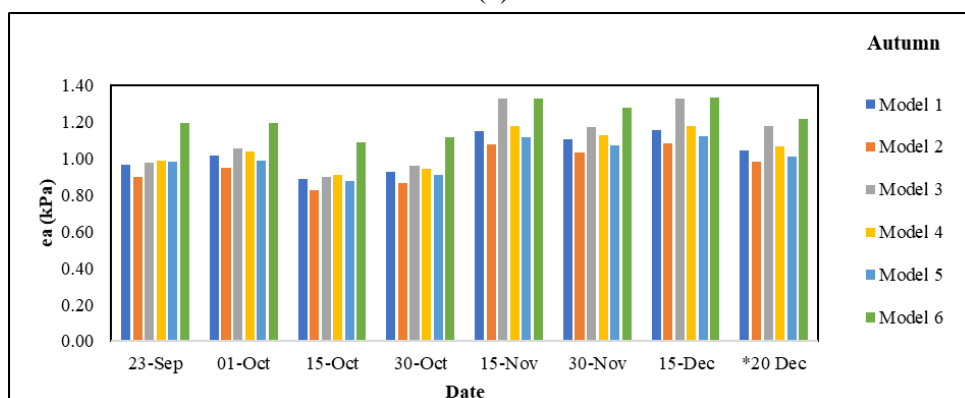
(a)
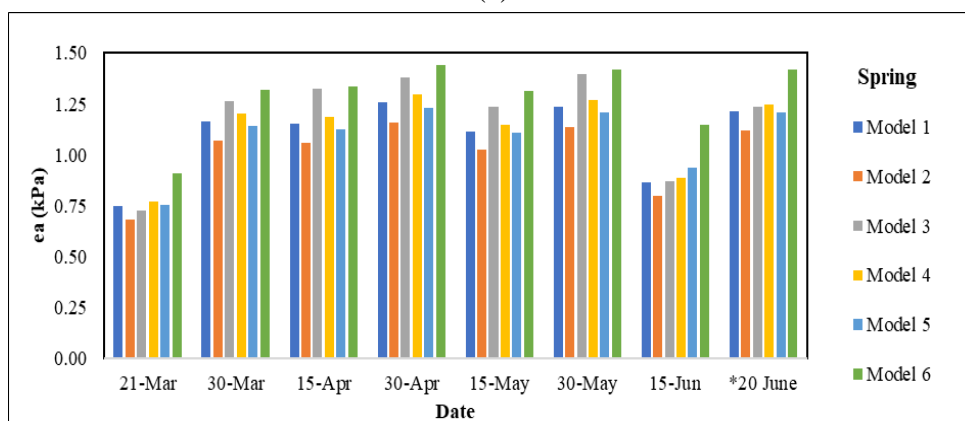
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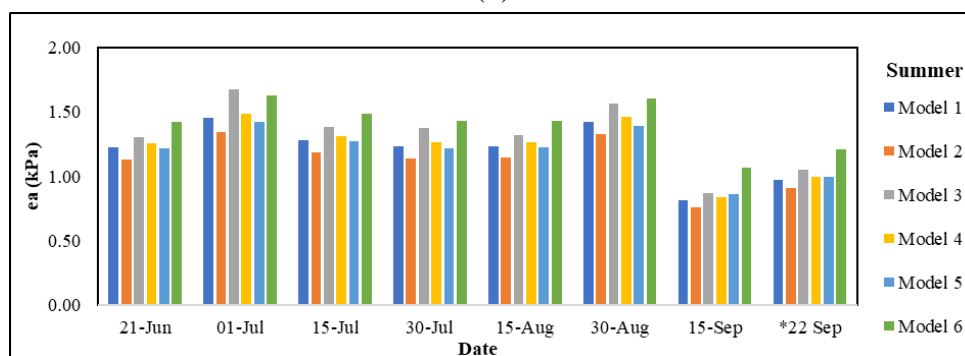
(c)

(d)

Figure 4. Comparison of daily values of actual vapour pressure calculated using the six vapour pressure models for the cropping periods
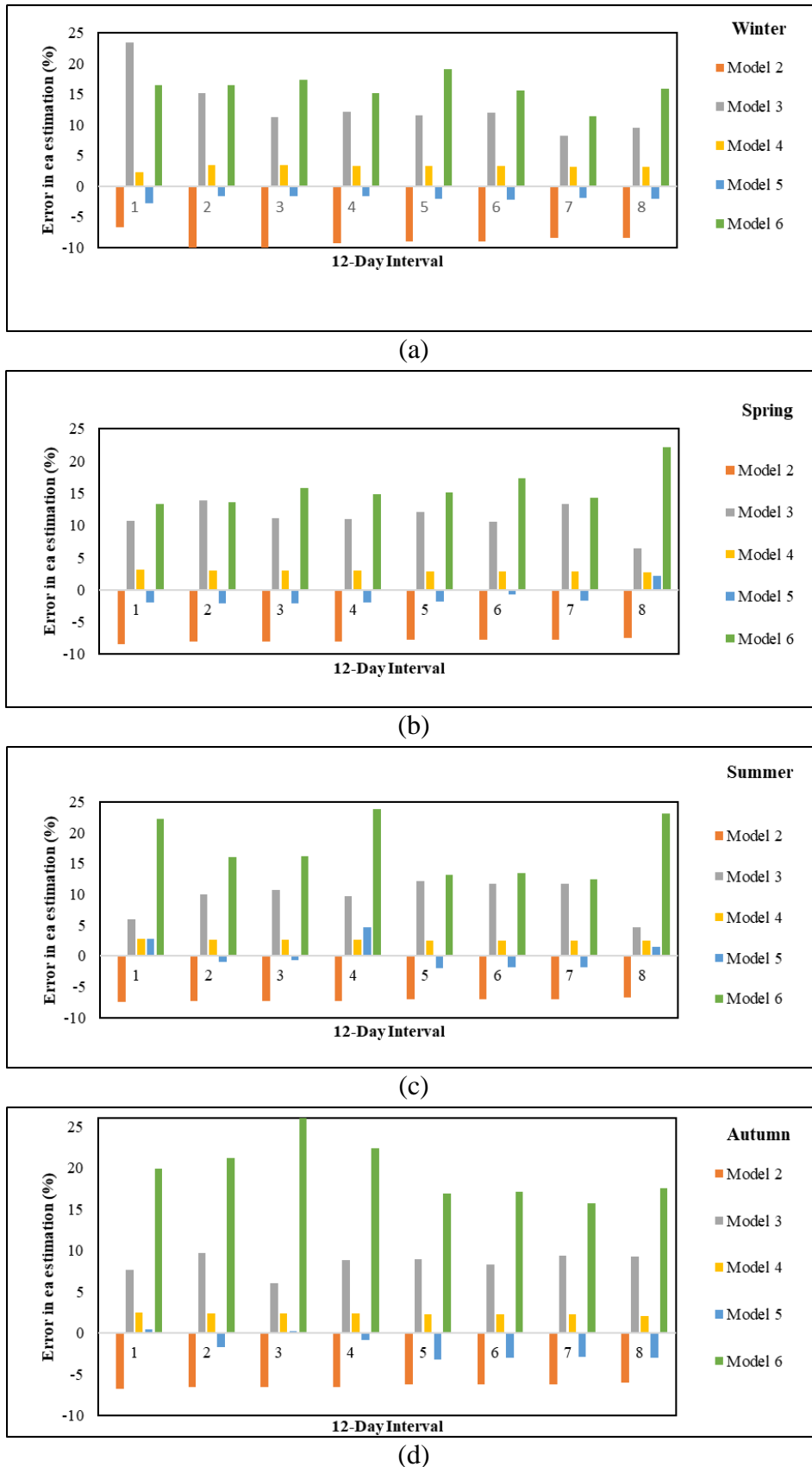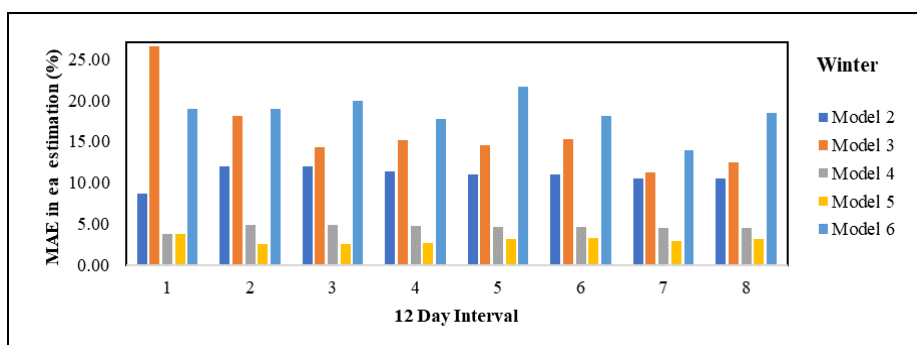
(a)

(b)

(c)

(d)

Figure 5. *Comparison of mean error (w.r.t. Model 1) in estimation of actual vapour pressure values for 12-day intervals*

However, on the basis of *Figure 5,* the relative accuracy of the VP models to determine daily actual vapour pressure values cannot be evaluated because they are the error values averaged for 12-day intervals, and negative and positive errors can cancel out each other to an extent. A better evaluation of the accuracy of the VP models is performed by comparing the absolute errors of the models in actual vapour pressure estimation. These daily absolute errors averaged for 12-day intervals (MAE) are shown in *Figure 6*. The Mean absolute error (MAE) values (w.r.t. Model 1) in the estimation of actual vapour pressure for 12-day intervals over the four seasons are shown in *Table 3*.

Table 3. Mean absolute error (MAE) values (w.r.t. Model 1) in the estimation of actual vapour pressure for 12-day intervals over the four seasons
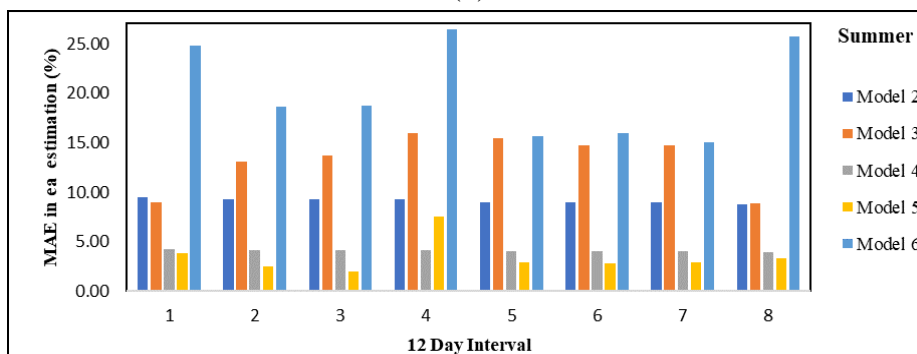
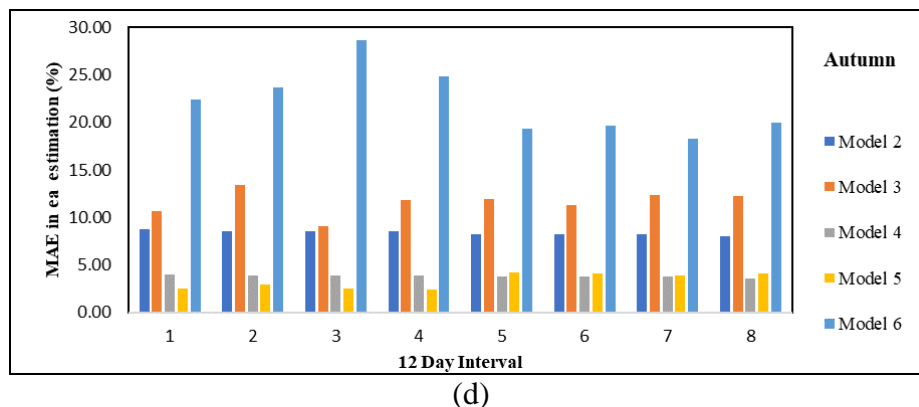| Models	Model 2	Model 3	Model 4	Model 5	Model 6
Maximum MAE (%)	12.00	26.49	4.91	7.49	28.66
Minimum MAE (%)	8.00	8.84	3.54	1.94	13.95
Average MAE (%)	9.57	13.74	4.24	3.21	19.73

(a)

(b)

(c)

(d)
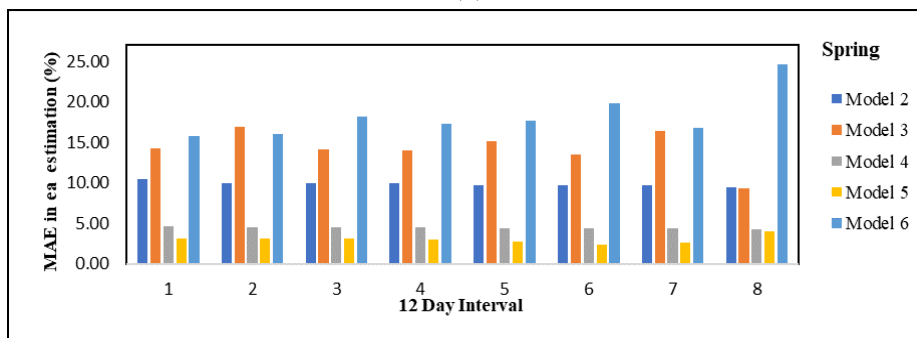
Figure 6. *Comparison of mean absolute error (w.r.t. Model 1) in estimation of actual vapour pressure values for 12-day intervals*

Comparative study of ETo estimates using six vapour pressure models

Vapour-pressure deficit (VPD) is an important parameter that is computed in evapotranspiration (ETo) models. Hence daily values of actual vapour pressure estimated by Models 1–6 were used to determine the reference (ETo) as required by FAO Penman-Monteith equation. The seasonal crop stage–wise sums of these daily ETo values for the four cropping seasons are tabulated in *Table 4*.

Table 4. *Comparison of ETo (mm/day) values estimated using the six vapour pressure models*

|		ETo(M1)	ETo(M2)	ETo(M3)	ETo(M4)	ETo(M5)	ETo(M6)
Winter	Initial	23.76	24.86	19.13	11.94	24.31	20.76
	Development	16.81	12.02	23.36	23.32	16.11	23.71
	Midseason	81.12	86.67	75.03	66.36	82.34	72.85
	Late season	46.33	50.67	41.81	39.02	47.37	39.35
	Overall season	168.02	174.22	159.33	140.64	170.12	156.67
Spring	Initial	28.83	30.79	26.26	23.79	29.30	25.90
	Development	48.75	51.92	43.61	40.85	49.58	43.06
	Midseason	105.03	110.42	97.06	95.31	106.17	94.69
	Late season	75.22	77.40	73.34	67.67	74.79	69.20
	Overall season	257.83	270.54	240.27	227.62	259.84	232.86
Summer	Initial	38.65	39.72	37.62	34.67	38.32	35.56
	Development	68.31	70.46	65.23	56.20	68.32	63.17
	Midseason	133.23	138.20	124.97	106.16	134.26	123.48
	Late season	86.68	88.68	85.02	70.87	86.41	80.26
	Overall season	326.87	337.06	312.84	267.90	327.31	302.47
Autumn	Initial	37.21	38.13	36.09	27.80	37.29	34.36
	Development	75.12	76.81	72.67	51.06	75.31	69.09
	Midseason	99.79	103.90	94.27	60.37	101.64	88.81
	Late season	40.54	42.72	36.94	23.06	41.61	34.44
	Overall season	252.67	261.56	239.97	162.28	255.85	226.71

It is evident from the reference evapotranspiration computation that all the models performs well enough if total value of ETo for the whole cropping season is taken into consideration. The close values of reference evapotranspiration ETo in *Table 4* as estimated based on six vapour pressure model show that the total value of ETo of a cropping season is not much affected by the choice of the VP model that is used to determine the daily actual vapour pressure values for the study area. The error in ETo estimation is highest for Model 4 (*Figure 7*), which shows the daily error averaged for 12-day intervals. From *Figure 7* it is evident that Model 2 most of the time overpredicts ETo, the reason being underprediction of actual vapour pressure values by model 2. Models 3–6 underpredict ETo as these overpredicted actual vapour pressure values. *Figure 8* shows the 12-day averages of daily absolute errors in ETo estimation. It is clearly observed in *Figure 8* that the performance of Model 5 is best among all VP models as the MAE values are the least for all the intervals for model 5. In *Figure 8,* both the maximum and minimum MAE values for a 12-day interval can be seen corresponding to Model 6, which further highlights the erratic estimation of actual vapour pressure and thus ETo by Model 6. *Table 5* shows the maximum, minimum, and average of the MAE values for all 12-day intervals across the four cropping seasons. It can be verified from *Table 5* that in data-constrained conditions, Model 5 is the most accurate VP model among the five models, followed by Model 3. Model 4, which uses only Tmean data (other models use Tmax and Tmin data) has the highest overall MAE of the five models. Though daily Tmean data are observed to be enough for the accurate estimation of daily values of actual vapour pressure, it results in relatively higher errors in ETo estimation as compared to the other models, which use both Tmax and Tmin. This is because the values of saturated vapour pressure are underestimated when only daily Tmean values are used (as in Model 4). However, there is significant variation in the estimated values of actual vapour pressure using the VP models; the choice of VP model does not affect the seasonal value of ETo considerably in this study.

Table 5. *Mean absolute error (MAE) values (w.r.t. Model 1) in the estimation of reference evapotranspiration for 12-day intervals over the four seasons*
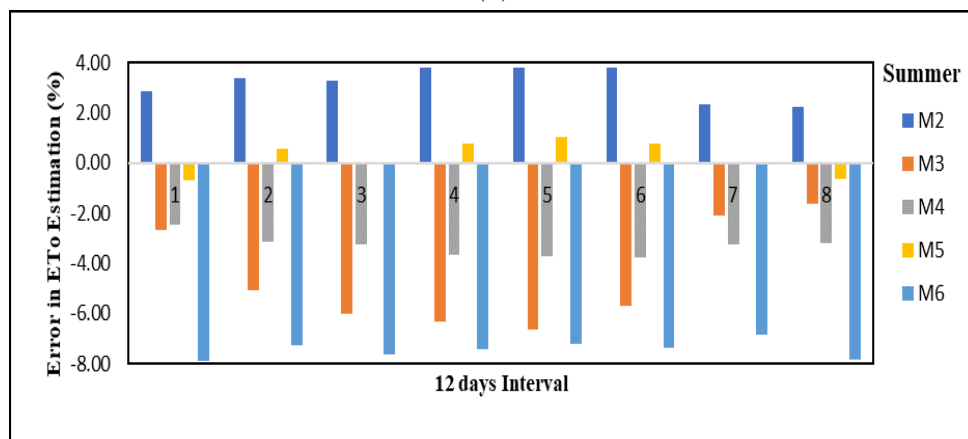
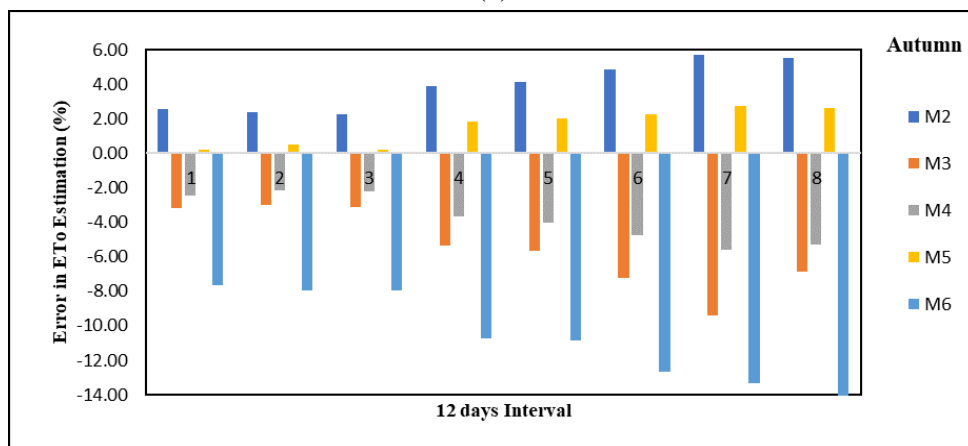| Models	Model 2	Model 3	Model 4	Model 5	Model 6
Maximum MAE (%)	12.27	13.69	10.13	5.67	15.71
Minimum MAE (%)	1.72	3.15	3.09	1.46	8.32
Average MAE (%)	6.19	7.63	5.35	2.78	10.78
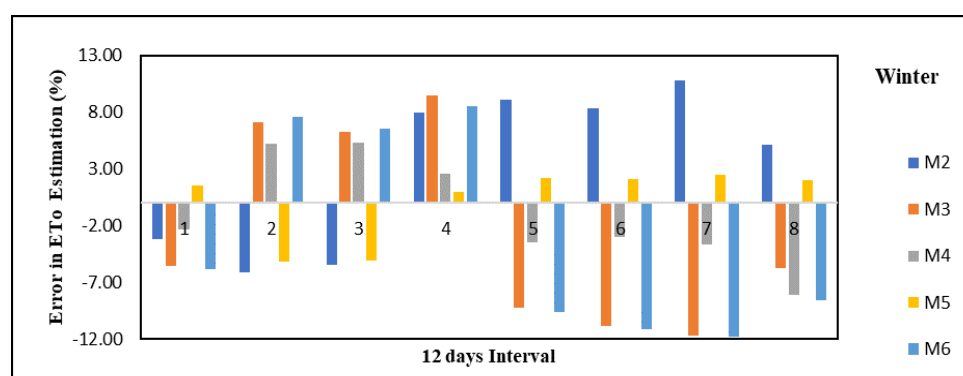
(a)
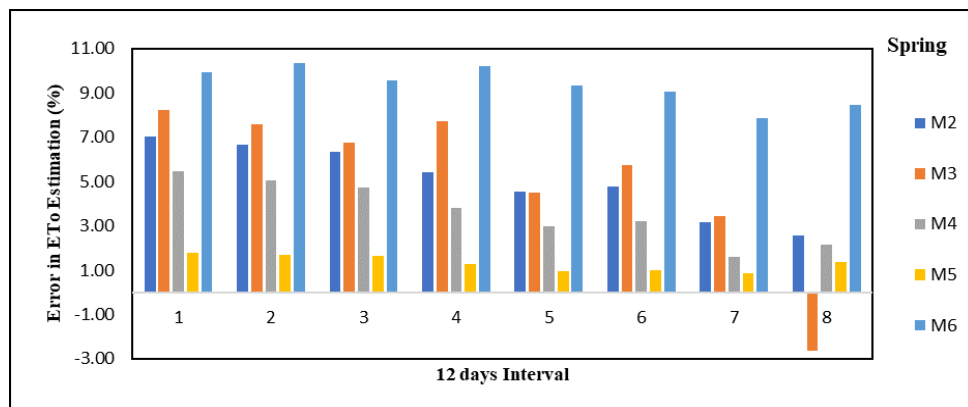
(b)

(c)

(d)

Figure 7. *Comparison of mean error (w.r.t. Model 1) in ETo estimation for 12-day intervals.*

Table 6. *Maximum and minimum wind speed for the four seasons*

Season	Max. wind velocity	Range	Min. wind velocity	Range
Winter	5.24		1.5	
Spring	2.99	Gentle to moderate	1.12	Light to slight
Summer	2.62		0.75	
Autumn	3.37		1.2	
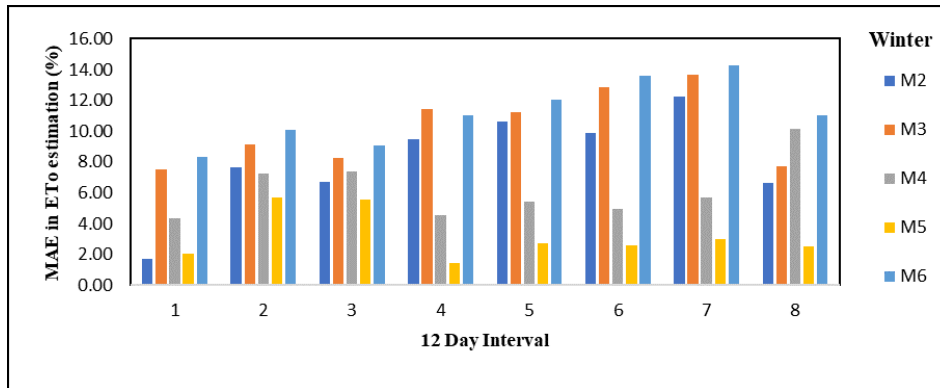
(a)
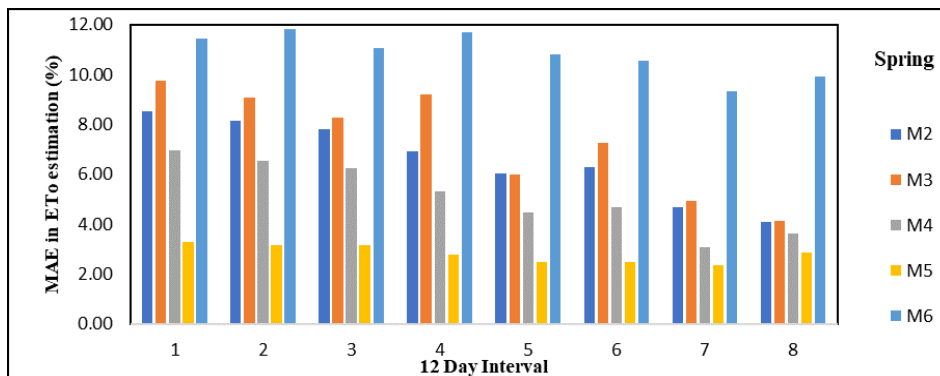
(b)
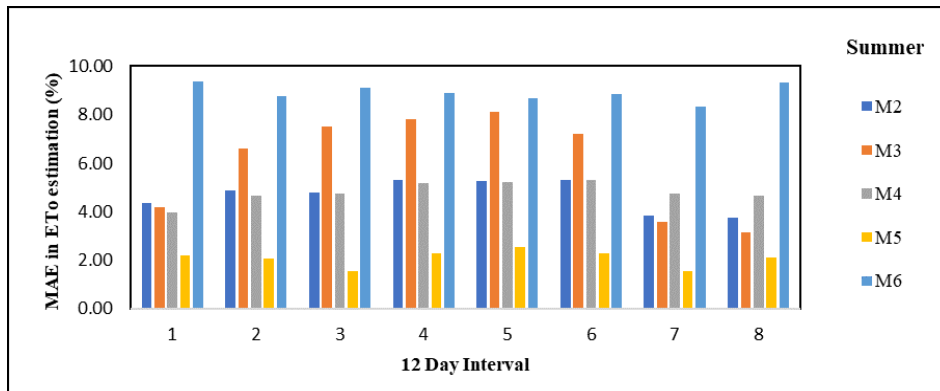
(c)

(d)

Figure 8. Comparison of mean absolute error (w.r.t. Model 1) in ETo estimation for 12-day intervals

Performance of the vapour pressure models with variation of wind velocity
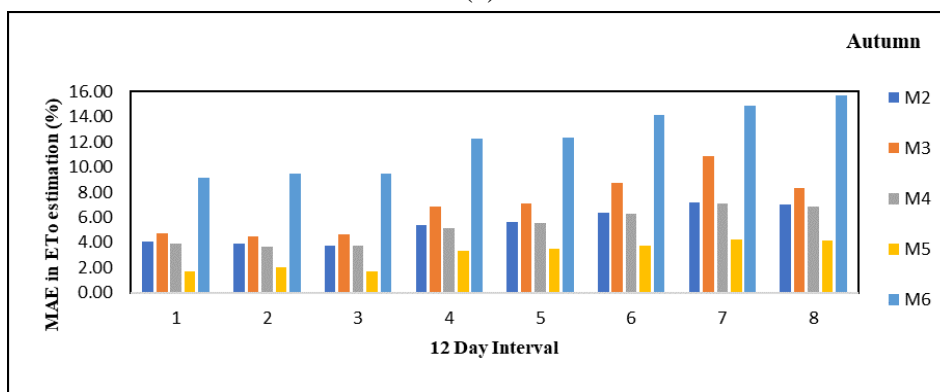
From the study, the performance of the five vapour pressure models (Models 2–6) is found to provide very reasonable result in ETo estimation for the four seasons for Abha region when compared to that of Model 1. The ETo values estimated provides satisfactory output even though there were relatively higher errors in the estimation of actual vapour pressure values. The reason may be due to the lower values of wind speed in the study area. As the ETo estimated from standard FAO Penman-Monteith method based on the product of wind speed (u_2) and vapour pressure deficit. The average wind speed data at 2 m height used in this study for ETo calculation by the FAO Penman-Monteith method are tabulated in *Table 6*.

According to Allen et al. (1998), the maximum wind speed values are in the category of gentle to moderate winds (2.62-5.24 m/s) while the minimum wind speed values falls under the category of light to slight winds (0.75-1.5 m/s). Therefore, in order to observe the effect of differences of result between higher wind speed values and lower wind speed values in the performance of VP models for ETo estimation. Taking all the parameters as before and wind speed data as shown in *Table 6* are used to determine the ETo. For all models (Models 2–6), the error in ETo estimation increased when higher values of wind speeds were used. This clearly shows that with the increase in wind speed, the error in the estimation of ETo values due to the error in the values of e_a or VPD values will increase. The performance of Model 5 is found satisfactory, followed by Model 3. All the other models have an average value of mean absolute error (*Figure 9*). Therefore, the accurate estimation of actual vapour pressure or VPD plays a key role in estimating ETo values accurately, although for light winds, this effect is much less and becomes pronounced when the wind speed is higher. Similar findings were observed by (Upreti and Ojha, 2018).

Ranking of vapour pressure model in global performance index

The statistical analysis was performed by considering ten parameters in order to judge the reliability of five vapour pressure model as compared to standard actual vapour pressure model 1 as shown in *Table 7*. The scaled values of statistical errors between 0 and 1 as described in *Table 8* and the GPI values for five models are shown in *Table 9*. In addition, the variation of GPI is also shown by *Figure 10*. The GPI value ranges from -4 to 2.771. Among 5 models, 2 models shows positive GPI value while 3 models have negative GPI as shown in *Figure 10*. The highest value of GPI is shown by Model 5. Hence it can be seen that GPI has simplified the statistical outcomes to identify the performance of models. *Table 9* shows the ranking of the models on the basis of their GPI values sorted in descending order, since the highest GPI value represent the best performing model.

Table 7. Estimated value of statistical indicator

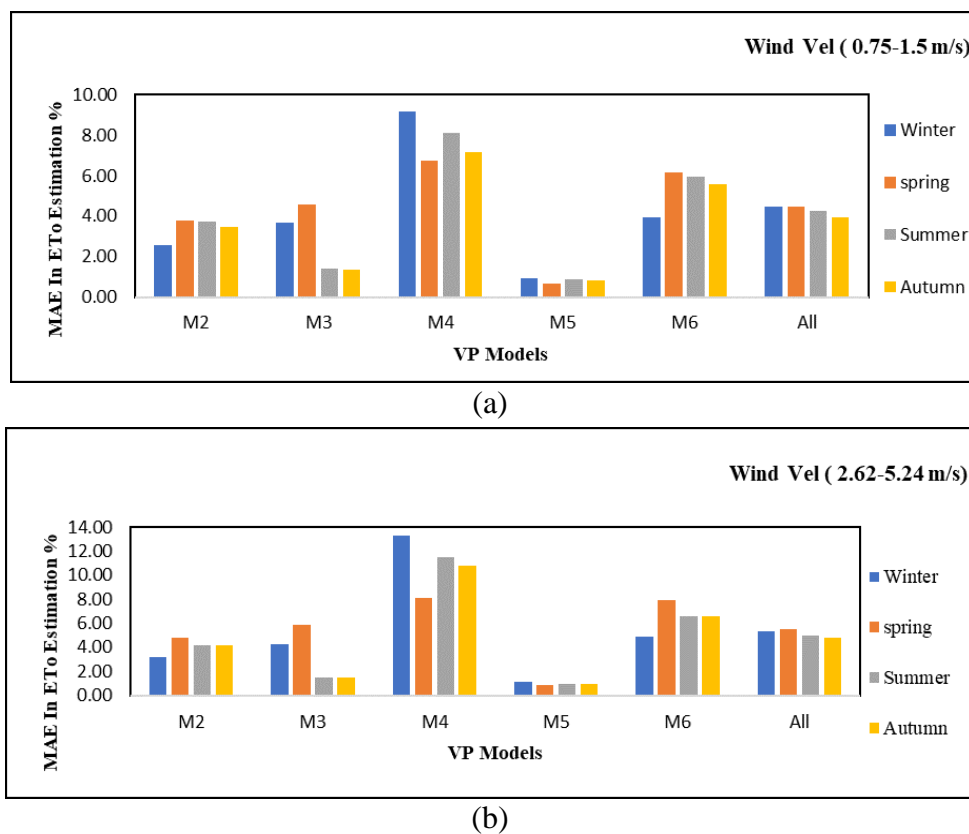|	MAE	RMSE	MARE	U95	RMSRE	RRMSE	MBE	R^2	ERMAX	TTEST
Model2	0.0854	0.0875	0.0754	0.1754	0.0763	0.0215	0.0854	0.9953	0.1000	85.8353
Model3	0.122	0.159	0.105	0.373	0.138	0.039	-0.121	0.855	1.319	22.000
Model 4	0.031	0.032	0.027	0.064	0.028	0.008	-0.031	0.990	0.034	84.176
Model 5	0.024	0.028	0.023	0.073	0.037	0.007	0.015	0.986	0.522	11.669
Model 6	0.189	0.193	0.175	0.387	0.189	0.047	-0.189	0.956	1.023	88.591

(a)

(b)

Figure 9. *Comparison of mean absolute error (w.r.t. Model 1) in daily ETo estimation for different wind speed ranges*
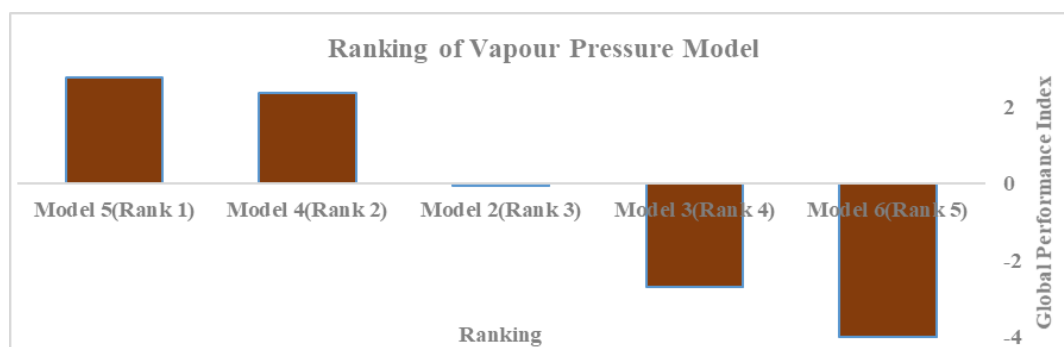

Figure 10. *Ranking of vapour pressure model*

Table 8. *Scaled (0-1) value of statistical indicator*

Model	Scaled									
	MAE	RMSE	MARE	U95	RMSRE	RRMSE	MBE	R^2	ERMAX	TTEST
Model2	0.373	0.359	0.346	0.346	0.302	0.359	1.000	1.000	0.051	0.964
Model3	0.596	0.795	0.543	0.958	0.681	0.795	0.248	0.000	1.000	0.134
Model 4	0.043	0.020	0.031	0.000	0.000	0.020	0.576	0.962	0.000	0.943
Model 5	0.000	0.000	0.000	0.030	0.059	0.000	0.743	0.934	0.380	0.000
Model 6	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.720	0.769	1.000

Table 9. *Global performance index and rank of five models*

Model	MAE	RMSE	MARE	U95	RMSRE	RRMSE	MBE	R²	ERMAX	TTEST	GPI	Rank
Model 5	0.373	0.359	0.346	0.316	0.243	0.359	-0.167	0.000	0.000	0.943	2.771	1
Model 4	0.331	0.339	0.316	0.346	0.302	0.339	0.000	-0.029	0.380	0.000	2.381	2
Model 2	0.000	0.000	0.000	0.000	0.000	0.000	-0.424	-0.066	0.328	-0.022	-0.051	3
Model 3	-0.222	-0.436	-0.197	-0.612	-0.379	-0.436	0.328	0.934	-0.620	0.808	-2.701	4
Model 6	-0.627	-0.641	-0.654	-0.654	-0.698	-0.641	0.576	0.214	-0.390	-0.057	-4.000	5

Discussion

This study investigated performance of vapour pressure models using weather data for Abha meteorological weather station in the computation of vapour pressure and evapotranspiration in Abha, Asir Region, Saudi Arabia. Effort has been made to compare six vapour pressure model during four seasons and ranking has been done using global performance index. The values estimated from different actual vapour pressure model were compared with the value obtained from standard model 1 which uses daily maximum and minimum values of temperature and RH, and is considered the most reliable model for determining the values of actual vapour pressure for four seasons (Allen et al., 1998). The daily percentage errors for actual vapour pressure were estimated for Models 2–6 averaged for 12-day intervals in the determination of actual vapour pressure. Based on error it was found that Model 2 generally underpredicts actual vapour pressure value. Models 3, 4, and 5 overpredicted the actual vapour pressure value. Model 6, which uses daily minimum temperature, has the most erratic behavior in estimating the actual vapour pressure value. The relative accuracy of the VP models to determine daily actual vapour pressure values cannot be evaluated because they are the error values averaged for 12-day intervals, and negative and positive errors can cancel out each other to an extent. A better evaluation of the accuracy of the VP models is performed by comparing the absolute errors of the models in actual vapour pressure estimation. The MAE for each of cropping season is much less for Models 4 and 5 as compared to the MAE values for Models 2, 3, and 6. Both Models 4 and 5 use daily RHmean and Tmean data for the estimation of actual vapour pressure values. Overall, the performance of Model 6 in the determination of actual vapour pressure values is the poorest among the five models. The lower MAE values for Models 4 and 5 indicate that these may be used for the determination of daily actual vapour pressure values in Abha regions with similar climates instead of Models 2 and 3, both of which the FAO-56 paper advised for use if all variables required for Model 1 were not available. Further daily values of actual vapour pressure estimated by Models 1–6 were used to determine the reference (ETo) as required by FAO Penman- Monteith equation. The seasonal crop stage–wise sums of these daily ETo values were used for the four cropping seasons. The error in ETo estimation is highest for Model 4, which shows the daily error averaged for 12-day intervals. Clearly, for all intervals, the maximum error in ETo estimation is for Model 4, even though the same model (along with Model 5) estimated the actual vapour pressure values most accurately. This can be attributed to the inaccurate determination of saturated vapour pressure values because the saturated vapour pressure value for Model 4 is determined differently from the other models. The better performance of Model 5 in ETo estimation also verifies this because both Models 4 and 5 determined actual vapour pressure values with similar accuracy. Therefore, the determination of daily saturated vapour pressure value should be done by equation of

saturated vapour pressure which uses both daily Tmax and Tmin instead of using equation in which only the daily Tmean value is used. It is evident that Model 2 most of the time overpredicts ETo, the reason being underprediction of actual vapour pressure values by model 2. Models 3–6 underpredict ETo as these overpredicted actual vapour pressure values. The performance of Model 5 is best among all VP models as the MAE values are the least for all the intervals for model 5. Both the maximum and minimum MAE values for a 12-day interval can be seen corresponding to Model 6, which further highlights the erratic estimation of actual vapour pressure and thus ETo by Model 6. Model 5 is the most accurate VP model among the five models, followed by Model 3. Model 4, which uses only Tmean data (other models use Tmax and Tmin data) has the highest overall MAE of the five models. Though daily Tmean data are observed to be enough for the accurate estimation of daily values of actual vapour pressure, it results in relatively higher errors in ETo estimation as compared to the other models, which use both Tmax and Tmin. This is because the values of saturated vapour pressure are underestimated when only daily Tmean values are used (as in Model 4). However, there is significant variation in the estimated values of actual vapour pressure using the VP models; the choice of VP model does not affect the seasonal value of ETo considerably in this study. The ETo values estimated provides satisfactory output even though there were relatively higher errors in the estimation of actual vapour pressure values. The reason may be due to the lower values of wind speed in the study area. As the ETo estimated from standard FAO Penman-Monteith method based on the product of wind speed (u2) and Vapour Pressure Deficit. For all models (Models 2–6), the error in ETo estimation increased when higher values of wind speeds were used. This clearly shows that with the increase in wind speed, the error in the estimation of ETo values due to the error in the values of ea or VPD values will increase. The performance of Model 5 is found satisfactory, followed by Model 3. All the other models have an average value of mean absolute error. Therefore, the accurate estimation of actual vapour pressure or VPD plays a key role in estimating ETo values accurately, although for light winds, this effect is much less and becomes pronounced when the wind speed is higher. Similar findings were observed by (Upreti and Ojha, 2018).

The performance of vapour pressure models was computed based on overall effect of evaluation criteria called as global performance index. The ranking was done in order to get most promising model which can be used alternative to model 1. From analysis it was evident that Model 5 provides best performance and model 6 worst.

Hence it is evident that actual vapour pressure is important parameter which is used for vapour pressure deficit which in turn used in reference evapotranspiration equation. VPD is an integrated variable for atmospheric water demand that depends on both air temperature and humidity, VPD will increase with ongoing climate warming, which suggests that atmospheric water demand or drought will also increase under such a scenario (Zhang et al., 2017). Therefore, it is necessary to investigate the relationship between increased VPD and crop yields on the regional or global scale. Lobell et al. (2013) indicated that increases in VPD contribute to water stress and affect crop growth and yield in two ways. First, the crops increase their demand for soil water to maintain carbon assimilation at a given rate; and second, the crops reduce the supply of soil water through elevated transpiration rates. Therefore, maize yield declined with increased VPD (Lobell et al., 2013). Shuai et al. (2013) found that VPD affected yield variability through its effects on water stress. Crops that were negatively related to VPD were usually located in areas where the mean VPD during the crop growing period was

higher. The changes in the sensitivity of crop yields to VPD can be attributed to changes in VPD itself, cultivars and agronomic management practices; for example, increasing crop sowing densities could increase crop sensitivity to VPD (Lobell et al., 2014). Adopting drought-tolerant cultivars and technologies, as well as increasing irrigation areas, might decrease the sensitivity of crop yields to VPD. The decline in reliability of water resources necessitates careful planning for water demand satisfaction under the highly variable demand characteristics in Saudi Arabia (Tarawneh and Chowdhury, 2018).

This study tries to explain the six-vapour pressure model in semi-arid region in Saudi Arabia. However, different regions show different behavior with respect to seasonal variability of rainfall, temperature change, agricultural activities, soil types and crop types. Future study must understand the overall implications of climate change in Saudi Arabia and investigate the possibility of scheduling and/or shifting crop producing periods.

Conclusions

The present research work deals with six vapour pressure models in order to determine six sets of daily values of actual vapour pressure for four seasons. The six sets of daily computed actual vapour pressure from six models were then used to compute ETo by standard FAO56 Penman-Monteith equation. The performance evaluation of the five models (Models 2–6) was analyzed by comparing the values of the estimates of actual vapour pressure and ETo with those of Model 1, which is recommended in the literature to determine daily actual vapour pressure values if all meteorological variables required are available using global performance index. From the research work it can be concluded that:

1. From global performance index, Models 5 and 4 have higher accuracy in the estimation of daily actual vapour pressure values with GPI Value of 2.77 and 2.38 respectively as compared to Models 2, 3 (vapour pressure models mentioned in FAO-56), and 6 with GPI value of -0.051,-2.7 and -4 respectively.

2. Daily Tmean values (Model 4) are found to be not good enough for the estimation of vapour pressure deficit because this underestimate the daily saturation vapour pressure, which results in underestimation of ETo. This highlights the importance of the requirement of daily Tmax–Tmin data for accurate estimation of daily ETo

3. The result obtained from global performance index shows that the performance of the Model 5, which is based on the Lawrence Tdew–RH relationship is closest to Model 1 in ETo estimation when compared to the other models. On the basis of this study, it is recommended to use Model 5 for estimation of actual vapour pressure and ETo when only daily RHmean data are available

4. The result with wind speed shows that error in actual vapour pressure with light winds do not affect ETo estimation much. However, the effect of actual vapour pressure values becomes significantly high on ETo estimation for higher wind speed ranges.

5. The results of this study could be used by water management system, crop cultivators, crop advisors, researchers and students from universities and

research centre. Moreover it can be benefitted by makers of decision and in the vast field of agriculture, hydrology and environment.

6. The present results demonstrated that atmospheric VPD played significant roles in modulating water movement along the soil-plant-atmospheric continuum, and these findings can be applied to greenhouse production. VPD regulation efficiently moderated plant water stress and maintained water balance by reducing the atmospheric driving force

Conflict of interests. The authors declare no conflict of interests.

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