Chapter 5
Vapor Pressure Calculation Methods

Abstract Evapotranspiration (ET) or water loss to the atmosphere is one of the largest components of the hydrologic cycle, and its estimation is subject to uncertainties. Most ET estimation methods depend on vapor pressure deficit estimation. Improvements in saturation vapor pressure, actual vapor pressure, and vapor pressure deficit computations contribute to reducing errors in estimating ET. Using high-resolution meteorological data, various vapor pressure computations methods were compared. High-resolution saturation vapor pressure can be computed from high-resolution meteorological data reflecting diurnal fluctuations. In the absence of high-resolution meteorological data, daily average saturation vapor pressure is best estimated from the daily 24-h average relative humidity and the 24-h average air temperature followed by the average of daily maximum and minimum air temperature. Actual vapor pressure is best estimated from the 24-h mean air temperature and relative humidity. With some error, the average of the maximum and minimum air temperature and relative humidity can be applied to estimate actual vapor pressure. In this study, application of many equations is presented with correlation of the results with "true" estimates.

Keywords Vapor pressure • Vapor pressure deficit • Vapor pressure calculation

5.1 Introduction

Most ET estimation models depend on the estimation of vapor content of the air, its capacity to hold more, and vapor pressure deficit (vpd). Vapor pressure deficit is a major factor in the rate and amount of mass transfer. The amount of water vapor in saturated air is dependent on the temperature of the mixture. The higher the temperature is, the higher the capacity to hold water vapor. Vapor pressure deficit is the difference between saturation vapor pressure and actual vapor pressure ($e_s - e_d$). Anderson (1936) and others realized early on that percent humidity by itself is not

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a measure of dryness but vapor pressure deficit. The selection of equations for the computation of e_s and e_d has direct effect on the calculation of vpd for use in ET estimation models.

Jensen et al. (1990) have presented ET models that rely on vpd and discussed the commonly used vapor pressure computation methods. Evaporation estimation methods such as Penman, Penman-combination, Penman–Monteith, Van Bavel–Businger, and mass transfer models have vapor pressure components. Sadler and Evans (1989) have discussed errors of ET estimation associated in vpd computation methods. Howell and Dusek (1995) summarized the literature concerning the application of diverse methods for computing vapor content of the air. They also compared vpd computation methods for the semiarid region of the Southern High Plains (Bushland, Texas).

5.2 Comparison of Vapor Pressure Computation Methods

5.2.1 Methods

Vapor pressure (e_d) is dependent on air temperature and humidity. The capacity of air to hold moisture increases as air temperature increases and vice versa. The diurnal variation of saturation vapor pressure follows the diurnal variations of air temperature. Vapor pressure (actual) is computed from saturation vapor pressure (e_s) and relative humidity. The difference between e_s and e_d is the vapor pressure deficit (vpd), which is a driver in the rate of evaporation. Saturation vapor pressure is computed as follows (Eq. 5.1):

$$e_s = 0.611 \exp\left(\frac{17.27T}{T + 237.3}\right) \tag{5.1}$$

where e_s is saturation vapor pressure in kPa and T (°C) is 24-h average air temperature or maximum air temperature, minimum air temperature, or average of daily maximum and minimum temperature depending on the equation selected to compute actual vapor pressure (e_d).

Eight methods of e_d computations were evaluated against a "true" e_d as computed from the difference of the "true" e_s and "true" vpd. "True" e_s was computed based on Eq. 5.2 from 15-min average air temperature:

$$e_s = \frac{1}{96}\sum_{i=1}^{96} 0.611 \exp\left(\frac{17.27T_i}{T_i + 237.3}\right) \tag{5.2}$$

where T_i is average air temperature in °C for the 15-min time interval, i, for the day. The "true" vpd was computed from "true" e_s and average relative humidity (RH). Daily vpd was computed, as shown in Eq. 5.3 (Monteith 1973).

$$\text{vpd} = e_s\left(1 - \frac{\text{RH}}{100}\right) \tag{5.3}$$

A "true" e_d is the difference between "true" e_s and "true" vpd. Six commonly used e_d estimation methods are presented as follows, and the daily estimates are compared to the "true" estimate. An equation used for estimating saturation vapor pressure is applied to estimate actual vapor pressure by using the daily minimum air temperature (Eqs. 5.4, 5.5, 5.6, 5.7, 5.8, and 5.9):

$$e_d = 0.611 \exp \frac{17.27T_{\min}}{(T + 237.3)} \tag{5.4}$$

where e_d is actual vapor pressure in kPa and $T_{\min}$ is the day's minimum temperature in °C.

$$e_d = e_s(T_{\text{avg24}})\frac{\text{RH}_{\text{avg24}}}{100} \tag{5.5}$$

where $e_s(T_{\text{avg24}})$ is saturation vapor pressure computed from the daily average air temperature (°C) and RH_{avg24} is the daily average humidity in percent.

$$e_d = e_s(T_{\min})\frac{\text{RH}_{\max}}{100} \tag{5.6}$$

where $e_s(T_{\min})$ is saturation vapor pressure computed from the daily minimum air temperature (°C) and $\text{RH}_{\max}$ is the daily maximum humidity in percent.

$$e_d = e_s(T_{\max})\frac{\text{RH}_{\min}}{100} \tag{5.7}$$

where $e_s(T_{\max})$ is saturation vapor pressure computed from the daily maximum air temperature (°C) and $\text{RH}_{\min}$ is the daily minimum humidity in percent.

$$e_d = e_s(T_{\text{avg2}})\frac{\text{RH}_{\text{avg2}}}{100} \tag{5.8}$$

where $e_s(T_{\text{avg2}})$ is saturation vapor pressure computed from the average of the daily minimum and maximum air temperature (°C) and RH_{avg2} is the daily average humidity in percent computed as average of the daily minimum and maximum relative humidity.

$$e_d = \frac{1}{2}\frac{e_s(T_{\min})}{100}\text{RH}_{\max} + \frac{1}{2}\frac{e_s(T_{\max})}{100}\text{RH}_{\min} \tag{5.9}$$

where e_d is computed as average of two methods presented earlier.

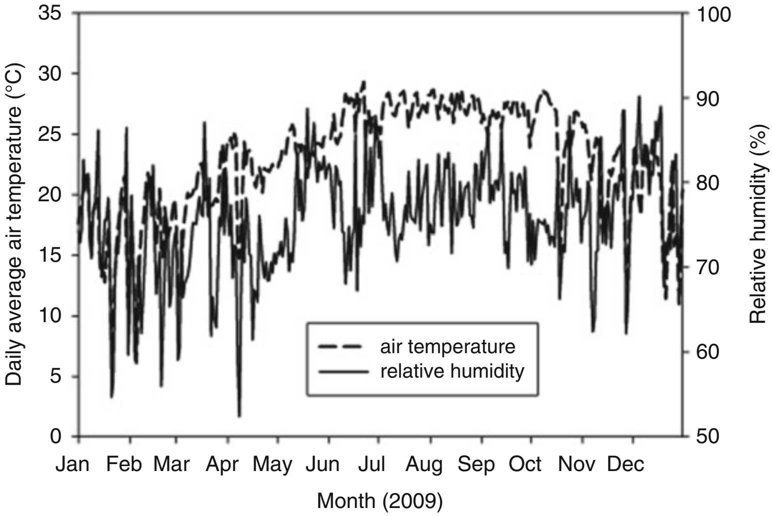

Fig. 5.1 High-resolution air temperature and relative humidity observations at a site in south Florida

5.2.2 Results

Mean daily saturation vapor pressure, actual vapor pressure, and vapor pressure deficit are dependent on air temperature, humidity data, and the selected equation. High-resolution air temperature and humidity data can be used to estimate "true" vapor pressure and compare the results to estimates from different equations and inputs. Figure 5.1 depicts air temperature and humidity daily variations at a site in south Florida (26° 38″ N, 80° 25″ W, elevation 3 m NGVD29) used to compute "true" vapor pressure. Data was acquired at a 2 m height with a HMP35C probe sampling every 5 min and recording 15-min average. The average air temperature and humidity for year 2009 were 22.9 °C and 76%, respectively.

Mean daily saturation vapor pressure, actual vapor pressure, and vapor pressure deficit estimates vary with the method of calculation. Methods of mean daily vpd computation that are more influenced by daytime temperature and humidity conditions overestimate mean daily vpd but better estimate mean daytime vpd. Stockle and Kiniry (1990) have reported that plant radiation-use efficiency is related to vpd. The daytime vpd computations could be important in plant water use, radiation-use studies, and plant growth models. Methods of vpd estimation are presented in Cuenca and Nicholson (1982), Sadler and Evans (1989), Jensen et al. (1990), and Howell and Dusek (1995).

Daily mean "true" e_s, e_d, and vpd as computed from 15-min time interval air temperature and humidity data are shown in Fig. 5.2 for a sample year. Estimation of daily average vpd depends on the estimation of the saturation vapor pressure and the actual vapor pressure. Both parameters depend on the selection of computation

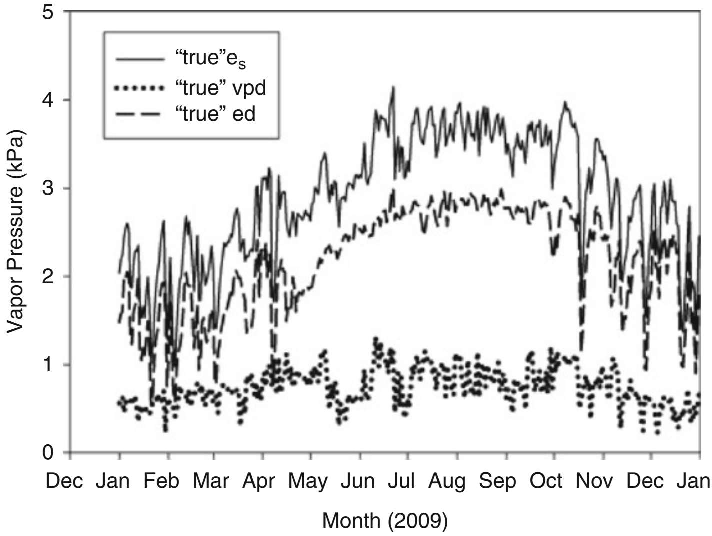

Fig. 5.2 "True" saturation (e_s), actual (e_d) vapor pressure, and vpd daily distribution for a site in south Florida

Table 5.1 Comparison of mean daily saturation vapor "true" e_s with values estimated by three equations

e_s	Mean (kPa)	Std (kPa)	a	b	r	$S_{y/x}$(kPa)
X "True" e_s	2.98	0.71	–	–	–	–
Y e_s (T_{avg24})	2.87	0.71	−0.03	1	1	0.04
Ye_s (T_{avg2})	2.94	0.76	−0.15	1.06	0.98	0.11
$Y1/2(e_s(T_{max}) + e_s(T_{min}))$	3.02	0.76	−0.06	1.06	0.98	0.12

equation. Table 5.1 depicts comparison of the "true" e_s computed from Eq. 5.2 with estimates of e_s computed with Eq. 5.1 with 24-h average temperature (T_{avg24}), with average of maximum and minimum daily temperature (T_{avg2}), and e_s as average of e_s computed using minimum daily temperature (T_{min}) and maximum daily temperature (T_{max}). The table compares means, standard deviation, and standard errors of estimates of the different methods and the "true" values. A regression statistic is provided to measure how well the different methods estimate vapor pressure.

The "true" average e_s for the analysis year of 2009 was 2.98 kPa with standard deviation of 0.71 kPa. A previous study reported a mean of 2.94 kPa and standard deviation of 0.63 kPa from 808 days of analysis (February 1993–April 1995) from the same site (Abtew 1995). The same study reported a mean daytime-to-nighttime vpd ratio of 8.7. As a comparison, a daytime-to-nighttime vpd ratio for the low-humidity, higher latitude and altitude region of the Southern High Plains (Bushland, Texas) was 3.21 ($n = 706$), as derived from Howell and Dusek (1995).

From Table 5.1, it is shown the method that uses the 24-h daily mean air temperature provides the best estimate compared to the other methods followed by

Table 5.2 Comparison of mean daily vapor pressure (actual) "true" e_d with estimates from five methods

e_d	Mean (kPa)	Std (kPa)	a	b	r	$S_{y/x}$ (kPa)
X "True" e_d	2.17	0.59	–	–	–	–
Y e_d (Eq. 5.4)	2.29	0.67	−0.06	1.09	0.96	0.13
Y e_d (Eq. 5.5)	2.19	0.60	0.01	1	1	0.03
Y e_d (Eq. 5.6)	2.08	0.63	−0.16	1.03	0.98	0.09
Y e_d (Eq. 5.7)	2	0.58	−0.03	0.94	0.96	0.16
Y e_d (Eq. 5.8)	2.19	0.6	0.01	1	1	0.03
Y e_d (Eq. 5.9)	2.04	0.59	−0.09	0.98	0.99	0.13

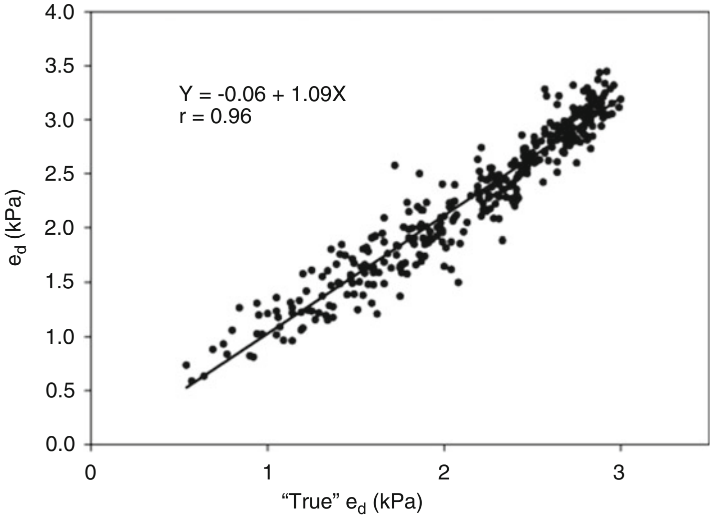

Fig. 5.3 Comparison of e_d computed with Eq. 5.4 and the "true" e_d

the method that uses average of the daily minimum and maximum air temperature. The least preferred method is average e_s computed from daily minimum and maximum air temperatures.

The "true" e_d was computed as a difference of the "true" e_s and the "true" vpd as computed with average daily humidity in Eq. 5.3. The mean and standard deviations were 2.19 and 0.6 kPa, respectively. Table 5.2 depicts comparison of the "true" e_d with e_d computed by Eqs. 5.4, 5.5, 5.6, 5.7, 5.8, and 5.9.

Comparison of actual vapor pressure computed with Eq. 5.4 and the "true" actual daily average vapor pressure is shown in Fig. 5.3 with a correlation coefficient of 0.92. The mean and standard deviation from this method are 2.29 and 0.67 kPa. The standard error of estimation is 0.13 kPa.

Comparison of actual vapor pressure computed with Eq. 5.5 and the "true" actual daily average vapor pressure is shown in Fig. 5.4 with a correlation coefficient of close to 1. The mean and standard deviation from this method are 2.19 and 0.60 kPa. The standard error of estimation is 0.03 kPa.

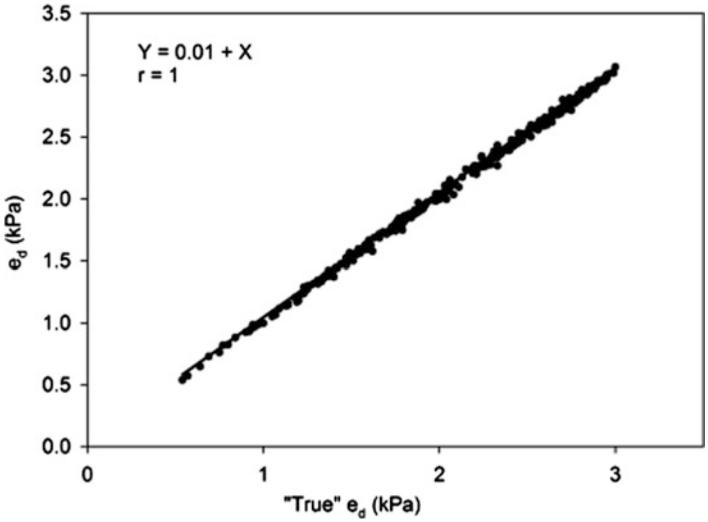

Fig. 5.4 Comparison of e_d computed with Eq. 5.5 and the "true" e_d

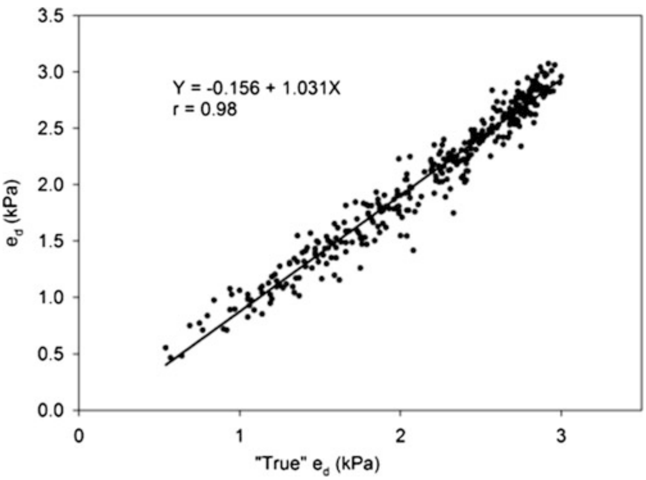

Fig. 5.5 Comparison of e_d computed with Eq. 5.6 and the "true" e_d

Comparison of actual vapor pressure computed with Eq. 5.6 and the "true" actual daily average vapor pressure is shown in Fig. 5.5 with a correlation coefficient of 0.96. The mean and standard deviation from this method are 2.08 and 0.63 kPa. The standard error of estimation is 0.09 kPa.

Comparison of actual vapor pressure computed with Eq. 5.7 and the "true" actual daily average vapor pressure is shown in Fig. 5.6 with a correlation coefficient of 0.92. The mean and standard deviation from this method are 2.00 and 0.58 kPa. The standard error of estimation is 0.16 kPa.

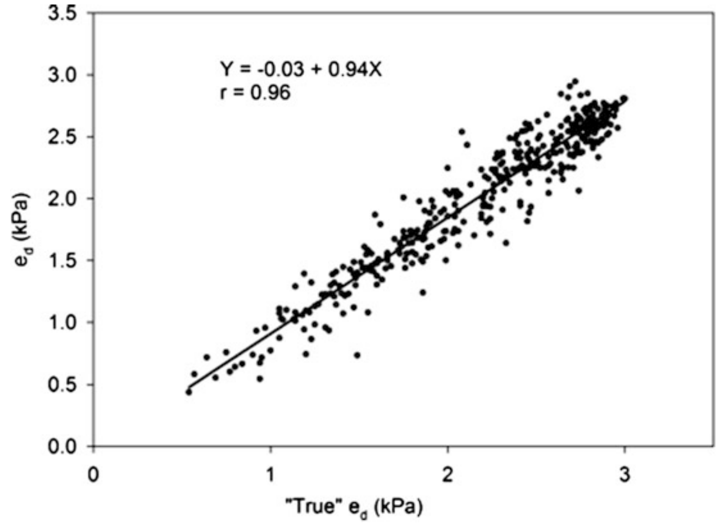

Fig. 5.6 Comparison of e_d computed with Eq. 5.7 and the "true" e_d

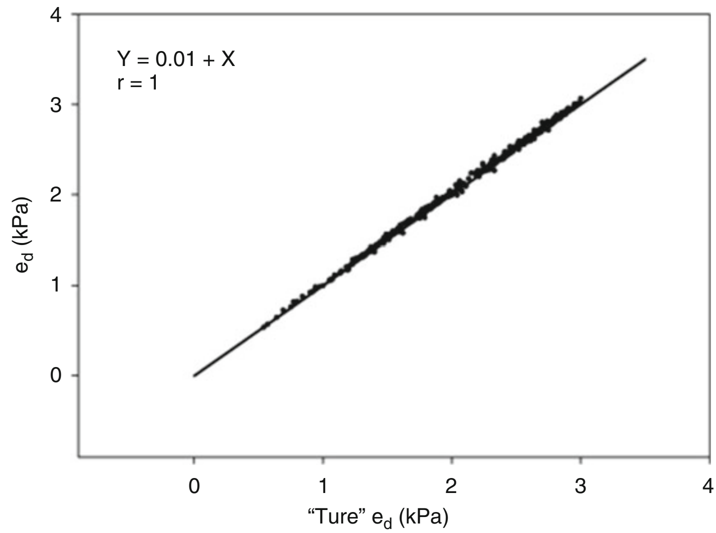

Fig. 5.7 Comparison of e_d computed with Eq. 5.8 and the "true"

Figure 5.7 depicts comparison of e_d computed with Eq. 5.8 and the "true" $e_{d.}$ The mean and standard deviation from this method are 2.19 and 0.6 kPa. The standard error of estimation is 0.03 kPa.

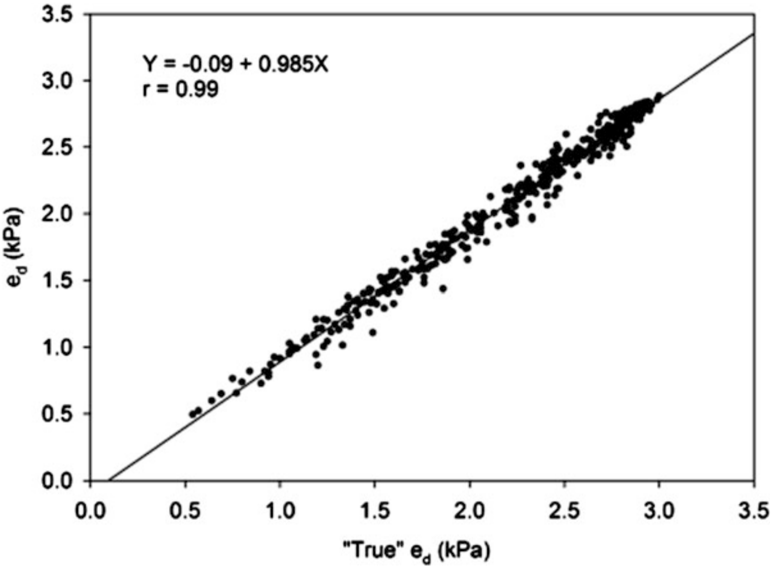

Fig. 5.8 Comparison of e_d computed with Eq. 5.9 and the "true" e_d

Figure 5.8 depicts comparison of e_d computed with Eq. 5.9 and the "true" e_d. The mean and standard deviation from this method are 2.04 and 0.59 kPa. The standard error of estimation is 0.13 kPa.

The best estimate of actual vapor pressure, e_d, is from Eq. 5.8 where both temperature and humidity are averages of the daily maximum and minimum respective readings and Eq. 5.5 where 24-h average temperature and humidity are needed.

5.3 Summary

Vapor pressure deficit is a parameter required in ET estimation equations. Understanding and evaluation of the relative accuracy of saturation and actual vapor pressure computation equations are essential for best result in ET estimation. In most cases, the high-resolution meteorological data used to compute the "true" vapor pressure deficit may not be available. A previous analysis based on 808 days and the current analysis for the humid and warm region of south Florida provided similar results. High-resolution saturation vapor pressure can be computed from high-resolution meteorological data reflecting diurnal fluctuations. In the absence of high-resolution meteorological data, daily average saturation vapor pressure is best estimated from the daily 24-h average temperature or the average of daily maximum and minimum air temperature.

Actual vapor pressure is best estimated from the 24-h mean air temperature and relative humidity. With some error, the average of the maximum and minimum air temperature and relative humidity can be applied to estimate actual vapor pressure when only such data is available.

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