BUREAU OF METEOROLOGY REFERENCE EVAPOTRANSPIRATION CALCULATIONS

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ABBREVIATIONS

ADAM	Australian Data Archive for Meteorology
ASCE	American Society of Civil Engineers
AWS	Automatic Weather Station
BoM	Bureau of Meteorology
CAHMDA	Catchment-scale Hydrological Modelling and Data Assimilation
CRCIF	Cooperative Research Centre for Irrigation Futures
FAO56-PM equation	United Nations Food and Agriculture Organisation's adapted Penman-Monteith equation recommended in *Irrigation and Drainage Paper No. 56 (*Allen et al. 1998)
ET_o	Reference Evapotranspiration
QLDCSC	Queensland Climate Services Centre of the BoM
SACSC	South Australian Climate Services Centre of the BoM
VICCSC	Victorian Climate Services Centre of the BoM

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ABSTRACT

Reference evapotranspiration (ET_o) data is valuable for a range of users, including farmers, hydrologists, agronomists, meteorologists, irrigation engineers, project managers, consultants and students. Daily ET_o data for 399 locations in Australia will become publicly available on the Bureau of Meteorology's (BoM's) website (www.bom.gov.au) in 2010. A computer program developed in the South Australian Climate Services Centre of the BoM (SACSC) is used to calculate these figures daily. Calculations are made using the adapted Penman-Monteith equation recommended by the United Nations Food and Agriculture Organisation (FAO56-PM equation). Inputs to the equation include temperature, relative humidity and wind speed data from BoM weather stations and satellite derived daily solar radiation data. In the proposed ET_o tables for each weather station, daily evaporation pan (E_{pan}) data are presented alongside ET_o data. E_{pan} data are often used to estimate ET_o and the methods and limitations of doing so are discussed, as is the issue of missing data.

INTRODUCTION

Evapotranspiration is the combined process of both evaporation from soil and plant surfaces and transpiration through plant surfaces (Burman et al. 1994). The rate of evapotranspiration is usually expressed in millimetres per unit time. Estimates of evapotranspiration from cropped land surfaces are vital for agricultural water management.

The evapotranspiration from a standardized vegetated surface can be represented by the reference evapotranspiration (ET_o). A panel of experts, convened by the United Nations Food and Agriculture Organisation in May 1990, recommended the adoption of the Penman-Monteith equation (FAO56-PM), as described in Allen et al. (1998), as the sole method for calculating ET_o. The standardized vegetated surface under consideration is a grass crop with a uniform height of 0.12 m, an albedo of 0.23 and a fixed surface resistance of 70 sm^{-1}, which is applicable to a moderately dry soil surface with an approximately weekly irrigation frequency.

Defining a reference surface enables comparison between ET_o data measured or calculated at different locations or in different seasons, because it refers to evapotranspiration from the same reference surface. Relating evapotranspiration to a particular surface also provides a reference to which evapotranspiration from other surfaces can be related and eliminates the necessity of defining a different evapotranspiration level for each crop and stage of growth.

The most commonly used procedure for estimating crop evapotranspiration (ET_c) from ET_o is to apply a crop coefficient K_c (ET_c= ET_o K_c) that takes into account the influences of characteristics that distinguish a field crop from the reference grass crop.

Because ET_o describes the evaporating capability of the atmosphere at a particular location and time of the year and does not incorporate crop characteristics and soil factors, it is a climatic parameter and can be calculated from meteorological data. The main meteorological variables affecting evapotranspiration are solar radiation, air temperature, humidity and wind speed.

THE FAO56-PM EQUATION

The FAO56-PM equation is

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T_{mean} + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where ET_o is the reference evapotranspiration ($mmday^{-1}$),
Δ is the slope of the saturation vapour pressure curve ($kPa°C^{-1}$),
R_n is the net radiation at the crop surface ($MJm^{-2}day^{-1}$),
G is the soil heat flux density ($MJm^{-2}day^{-1}$),
γ is the psychometric constant ($kPa°C^{-1}$),
T_{mean} is the mean daily air temperature at a height of 2m (°C),
u_2 is the wind speed at a height of 2m (ms^{-1}),
e_s is the mean saturation vapour pressure (kPa), and
e_a is the actual vapour pressure (kPa).

The algorithm for the calculation of ET_o given by Eq. (1) is summarised in Box 11 (Chapter 4, Page 3) of Allen et al. (1998). A computer program based on this algorithm was developed in the South Australian Climate Services Centre of the Bureau of Meteorology (SACSC) by Bruce Brooks and updated by Bob Schahinger in 2008 to calculate ET_o using data from Bureau of Meteorology (BoM) weather stations and satellite derived daily solar radiation data. The program was validated using the numerical example provided in Example 17 (Chapter 4, Page 5) of Allen et al. (1998). The equivalent equations used in the SACSC computer program to calculate the components of Eq. (1) are presented below.

Slope of saturation vapour pressure curve (Δ)

When air is enclosed above an evaporating water surface, an equilibrium is reached between water molecules escaping and those returning to the water reservoir. The air is then said to be saturated since it cannot store any additional water molecules and the corresponding pressure is called the saturation vapour pressure. The number of water molecules that can be stored in the air depends on the temperature (T), such that the higher the air temperature, the higher the storage capacity, and thus the higher its saturation vapour pressure. In a graph of saturation vapour pressure vs. temperature, the slope of the curve (Δ) changes exponentially with temperature. It is an important parameter in describing vaporization and is obtained from

$$\Delta = \frac{4098\ [0.6108\ \exp\left[\frac{17.27\,T_{mean}}{T_{mean} + 237.3}\right]]}{(T_{mean} + 237.3)^2} \qquad (2)$$

where Δ is the slope of the saturation vapour pressure curve at T_{mean} ($kPa^{o}C^{-1}$),
and T_{mean} is the mean daily air temperature at a height of 2m (°C).

where T_{mean} is obtained from

$$T_{mean} = \frac{T_{\max} + T_{\min}}{2} \qquad (3)$$

where T_{max} and T_{min} are the daily maximum and minimum air temperatures (°C).

Net radiation at the reference crop surface (R_n)

$$R_n = R_{ns} - R_{nl} \qquad (4)$$

where R_n is the net radiation ($MJm^{-2}day^{-1}$),
R_{ns} is the net incoming shortwave radiation ($MJm^{-2}day^{-1}$), and
R_{nl} is the net outgoing longwave radiation ($MJm^{-2}day^{-1}$).

During the day R_n is usually positive and during the night it is usually negative. The total daily value of R_n is almost always positive (the exception being in extreme conditions at high latitudes). Net incoming shortwave radiation is calculated using

$$R_{ns} = (1-\alpha)R_s \qquad (5)$$

where α is the albedo of the grass reference crop = 0.23, and
R_s is the global solar exposure ($MJm^{-2}day^{-1}$).

Global solar exposure is the total amount of solar energy (both direct and diffuse) falling on a horizontal surface of unit area at the Earth's surface. Typical values of daily global solar exposure range from 1 to 35 MJm^{-2}. The highest values usually occur in clear sky conditions during summer and the lowest usually occur during winter or on very cloudy days.

Net longwave radiation is the difference between incoming and outgoing longwave radiation. As the outgoing longwave radiation is almost always greater than the incoming longwave radiation, R_{nl} generally represents an energy loss. The Stefan-Boltzmann law states that the amount of energy radiated per unit time from a unit surface area of an ideal black body is proportional to the fourth power of the absolute temperature of the black body (Glickman, 2000). However, the net energy flux leaving the earth's surface is less than that given by the Stefan-Boltzmann law due to the fact that some energy is absorbed and radiated downwards from the sky. Because humidity and cloudiness are particularly important, they are taken into account in Eq. (6). Although there are other absorbers and emitters of longwave radiation in the atmosphere, such as carbon dioxide and dust, an assumption is made in Eq. (6) that their concentrations are constant. Net longwave radiation is calculated using

$$R_{nl} = \sigma\left(0.34 - 0.139\sqrt{e_a}\right)\left(1.35\frac{R_s}{R_{so}} - 0.35\right)\left(\frac{T_{\max K^4} + T_{\min K^4}}{2}\right) \qquad (6)$$

where σ is the Stefan-Boltzmann constant = 4.903 x 10^{-9} ($MJK^{-4}m^{-2}day^{-1}$),
$T_{max,K}$ is the max absolute temperature in the 24-hour period (K=°C+273.16),
$T_{min,K}$ is the min absolute temperature in the 24-hour period (K=°C+273.16),
e_a is the actual vapour pressure (kPa),
R_s/R_{so} is the relative shortwave radiation (limited to ≤ 1.0),
R_s is the global solar exposure ($MJm^{-2}day^{-1}$), and
R_{so} is the clear-sky solar radiation ($MJm^{-2}day^{-1}$), which may be calculated using

$$R_{so} = (0.75 + 2\times10^{-5} z_e)R_a \qquad (7)$$

where z_e is the station elevation above sea level (m), and
R_a is the extraterrestrial radiation ($MJm^{-2}day^{-1}$), which can be estimated using the solar constant, the solar declination and the time of the year using

$$R_a = \frac{24\times60}{\pi} G_{sc} d_r [\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)] \qquad (8)$$

where G_{sc} is the solar constant = 0.0820 $MJm^{-2}min^{-1}$,
d_r is the inverse relative distance Earth-Sun,
ω_s is the sunset hour angle,
φ is the latitude in radians, and
δ is the solar declination, which is the latitude at which the Sun is directly overhead (Ladson, 2008).

The inverse relative distance Earth-Sun can be calculated using

$$d_r = 1 + 0.033\cos(\frac{2\pi}{365} J) \qquad (9)$$

where J is the Julian day, which is the number of the day in the year between 1 (January 1st) and 365 or 366 (December 31st).

The sunset hour angle can be calculated using

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)] \qquad (10)$$

where φ is the latitude in radians (which must be negative for the southern hemisphere) = π/180 (latitude in decimal degrees), and
δ is the solar declination, which can be calculated using

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right) \qquad (11)$$

where J is the Julian day.

Actual vapour pressure (e_a) derived from relative humidity data

Actual vapour pressure is the vapour pressure exerted by the water in the air. When the air is not saturated, the actual vapour pressure will be lower than the saturation vapour pressure. The difference between the saturation and actual vapour pressures is called the vapour pressure deficit (VPD). It is not possible to directly measure the actual vapour pressure but it can be derived from relative humidity data using

$$e_a = \frac{e_o(T_{\min})\frac{RH_{\max}}{100} + e_o(T_{\max})\frac{RH_{\min}}{100}}{2} \qquad (12)$$

where e_a is the actual vapour pressure (kPa),
RH_{max} and RH_{min} are the daily max and min relative humidities (%), and
e_o is the saturation vapour pressure (kPa), which can be calculated using

$$e_o(T) = 0.6108 \exp\left[\frac{17.27T}{T + 237.3}\right] \qquad (13)$$

Mean daily saturation vapour pressure (e_s):

Due to the non-linearity of Eq. (13), the mean saturation vapour pressure for a day should be computed as the mean of the saturation vapour pressures at the mean daily maximum and minimum air temperatures using

$$e_s = \frac{e_o(T_{\min}) + e_o(T_{\max})}{2} \qquad (14)$$

where e_o can be calculated using Eq. (13).

Soil Heat Flux

For calculations made for time periods between one and ten days, the soil heat flux, G, is generally ignored, that is the energy stored in the soil will be about the same at the start and end of the period and the net energy flux is very close to zero (Ladson, 2008). Hence G is set to zero in BoM daily ET_o calculations.

Psychometric constant

The psychometric constant, γ, is not in fact constant, since it depends upon air pressure, humidity, and temperature (Ladson, 2008). However it is approximately constant for a common range of conditions and is usually defined as

$$\gamma = \frac{c_p P}{\varepsilon \lambda} = 0.665 \times 10^{-3} P \qquad (15)$$

where c_p is the specific heat of air at constant pressure, which is dependent upon the humidity of the air, but is commonly taken to be 1.013×10^{-3} $MJkg^{-1o}C^{-1}$,

λ latent heat of vaporisation of water = 2.45 $MJkg^{-1}$,

ε ratio of molecular weight of water vapour to dry air = 0.622,

P atmospheric pressure (kPa) which, for a particular elevation of a weather station above sea level z_e, can be calculated using

$$P = 101.3\left(\frac{293 - 0.0065 z_e}{293}\right)^{5.26} \qquad (16)$$

Wind speed

Wind speed is lowest at the Earth's surface (due to surface friction) and increases with height. BoM anemometers are installed at two different standard heights. The <3m observations are normally made in conjunction with evaporation readings, with the anemometer only about 2m above ground level. The >3m observations are normally made at a height of 10m. For the FAO-56 PM equation wind speed data from a height of 2m above the ground is required. A logarithmic wind speed profile can be used to adjust wind speed data measured at a height of 10m via the following equation:

$$u_2 = u_z \frac{4.87}{\ln(67.8 \times z - 5.42)} \qquad (17)$$

where u_2 average daily wind speed (for 24-hour period beginning at midnight) at a height of 2m (ms^{-1}),

u_z average daily wind speed at a height of z (ms^{-1}), and

z height of original wind measurement (m).

THE INPUT DATA

The ET_o calculations delivered through the BoM are made using screened and quality-checked daily weather observations obtained from BoM weather stations and satellite derived solar radiation data. These are discussed below.

Solar radiation data

Daily global solar exposure values are for the 24-hour period beginning at midnight. Global solar exposure is the total amount of solar energy falling on a horizontal surface (BoM, 2009). The daily global solar exposure is the total solar energy for a day. Typical values for daily global solar exposure range from 1 to 35 MJm^{-2}. The values are usually highest in clear sun conditions during summer, and lowest during winter or on very cloudy days. Daily global solar exposures at ground level are not measured at the site of every weather station but can be derived from satellite data for the geographical location of any station using a physical model developed at the BoM Research Centre (as described in Weymouth et al. 2001).

Solar exposure data is derived from satellite imagery from geostationary meteorological satellites positioned over the western Pacific Ocean. The satellite currently in use is MTSAT-1R, operated by the Japanese Meteorological Agency. In the past images from the GMS-4 and GMS-5 satellites, operated by the Japanese Meteorological Agency, and the GOES-9 satellite, operated by the USA's National Oceanic & Atmospheric Administration (NOAA), have been used.

The MTSAT-1R satellite captures an image every hour in the visible and near infrared spectral bands, which cover the range 0.5 to 0.7 µm (visible (VIS)) and 0.7 to 1.1 µm (near infrared (NIR)). The images are divided into pixels, each of which covers an area of 1.25 by 1.25 km at the sub-satellite point (the point on the earth's surface directly beneath the satellite) and a larger area at mid-latitudes.

To estimate the daily global solar exposure at each location, the hourly satellite images are averaged over at least four pixels and integrated over the entire day. The irradiance at the earth's surface can be calculated from the irradiance at the top of the earth's atmosphere, the amount absorbed in the atmosphere (dependent upon the amount of water vapour present), the amount reflected from the surface (surface albedo) and the amount reflected from clouds (cloud albedo). Other small influences include ozone absorption and Rayleigh (or molecular) scattering.

The largest source of error in the model is in the calculation of reflected radiance. Because cloud tops are irregularly shaped, the reflected irradiance from a particular cloud may vary with the relative positions of the sun and the satellite, introducing an error of approximately 5% into the model. The second largest source of uncertainty (approximately 2%) is in the estimation of water vapour in the atmosphere, which involves numerical predictions and data from radiosondes as input into the model. Although it may also introduce a small error into the calculations, the drift in satellite calibration occurs slowly over time and can be easily corrected. Other factors contribute a combined total of less than 1% to the overall uncertainty of the model.

BoM scientists have used radiant exposure measurements made at ground level at the Bureau's radiation network stations to test the algorithm and calibrate model parameters. Each month a linear regression is performed on the satellite and surface data, generating a mean country-wide bias as a linear function of exposure which is used to adjust model output. For all data combined, the mean absolute value of the satellite-surface difference cycles from about 0.8 MJm^{-2} in winter to about 1.5 MJm^{-2} in summer.

A comparison between daily solar exposure data derived from GMS-5 satellite images and pyranometer data from July and August 1997 from 12 network sites showed that on average the model agreed with the measurements to within 0.17%, or around 0.04 MJm^{-2} on a typical clear day (BoM 2009), while the majority of measurements were found to agree within 6% (around 1.5 MJm^{-2} on a typical clear day). The satellite method tends to slightly over-estimate the radiant exposure in wet, cloudy conditions and to under-estimate it in dry conditions. On the basis of these and subsequent inter-comparisons it is concluded that the satellite model provides useful daily global solar exposure estimates in all conditions, with an error of 7% or better in clear sky conditions and up to 20% in cloudy conditions (BoM 2009). As a general rule, pyranometer measurements should be used if they are available within 40 km of the site where the solar radiation is to be estimated, otherwise satellite derived data should be used (Ladson, 2008).

Daily global solar exposure data derived from images from the MTSAT-1R satellite is of slightly lower quality than data derived from images from the GMS-5 satellite. This can be attributed to the difference in characteristics of the MTSAT-1R imager compared to the GMS-5 imager. Grant (private communication 2009) indicated that there was a mean absolute error in bias-corrected daily global solar exposure of 0.8 MJm^{-2} in late 2006 and a mean absolute error in bias-corrected daily global solar exposure of 1.2 MJm^{-2} over the period Spring to Autumn in recent years.

Air temperature data

Air temperature is measured in a Stevenson Screen at a height of 1.2 m above the ground. Maximum and minimum temperatures for the previous 24 hours are nominally recorded at 9 am local clock time. Minimum temperature is recorded against the day of observation, and the maximum temperature against the previous day.

Relative humidity data

Daily maximum and minimum relative humidity values are calculated from half-hourly or hourly relative humidity data, which is calculated from half-hourly (where available) or hourly temperature and dew-point data for the 24-hour period beginning at midnight using

$$RH = 100\frac{e_a}{e_o(T)} \quad (18)$$

Actual vapour pressure in equation (18) is calculated using

$$e_a = 0.6108\exp\left[\frac{17.27T_{dew}}{T_{dew} + 237.3}\right] \quad (19)$$

where T_{dew} = dew-point (^oC).

Saturation vapour pressure in equation (18) is calculated using

$$e_o = 0.6108\exp\left[\frac{17.27T}{T + 237.3}\right] \quad (20)$$

Sources of bias in input data

Data input to the SACSC computer program comes from the Australian Data Archive for Meteorology (ADAM). Daily climatic variables in meteorological databases are subject to several different sources of error (Hupet et al., 2001). One source is the error due to the sensor properties, the instrument settings or the instrument drift. A second source of error is due to the estimation of climatic variables from other, less accurate available meteorological data (e.g. the estimation of solar radiation from percent sunshine hours or percent sky cover). A third source of error which impacts the estimation of daily mean, and which is not often cited in the literature, is due to the temporal sampling frequency of the climatic data.

Sensors at BoM weather stations are maintained to the accuracies detailed in Table I. by maintenance visits at least twice a year.

Table I. Accuracies of BoM weather station sensors.

Sensor	**Range**	**Accuracy**	**Unit**
Air Pressure	750 to 1060	0.3	hPa
Air Temperature	-25 to +60	0.3	^oC
Wet Bulb Temperature	-25 to +60	0.3	^oC
Relative Humidity	2 to 100	3	%
Wind Speed	2 to 180	2	knots
Rainfall	0 to 999.8	2%	mm

Hupet et al. (2001) found that the climatic variables most impacted by bias due to inappropriate temporal sampling are solar radiation and wind speed, with maximum daily relative errors of 41% and 18%, respectively. The two climatic variables that were found to have the greatest impact on the estimation of daily ET_o were solar radiation and maximum temperature. However, it was also found that the estimation error due to inappropriate sampling for the cumulated ET_o was relatively small, reaching 3.8% for less intensive temporal sampling (one measurement per hour). None-the-less they concluded that this value is not negligible for “reference” methods.

The structure of Eq. (1) implies that apart from wind speed and air temperature, none of the other inputs appear explicitly in the calculation of ET_o. Although air temperature (T_{mean}) is present in the second term of the numerator, other elements of Eq. (1) also depend on temperature, i.e. using Eq. (1) requires converting measured parameters into a number of estimated parameters. Table II shows the relationships between measured climate variables and estimated parameters of Eq. (1).

Table II. Input data required to compute parameters of the FAO56-PM equation.

Parameter	**Input data**
u_2	u_z, z
e_s	T_{max}, T_{min}
e_a	T_{max}, T_{min}, RH_{max}, RH_{min}
Δ	T_{max}, T_{min}
γ	z_e
R_n	R_s, φ, J, z_e, T_{max}, T_{min}, RH_{max}, RH_{min}

MISSING DATA

Feedback from a group of trial users of the daily ET_o calculations suggests that from time to time there is an issue of misleading results caused by missing solar radiation data in particular. Currently, on days when solar radiation data is missing, a value of zero is used in calculations. This results in an incorrect ET_o value for the day. Some improvements that have been proposed are as follows: an alert of the occurrence of missing data; replacing the zero with a "-", which would cause an error in the equation and not provide an ET_o value for the day; or the insertion of patched solar radiation data. There is merit in avoiding generation of incorrect ET_o values due to missing data because those who do not scrutinise the data carefully might be misled.

PAN EVAPORATION DATA

Although calculating ET_o using E_{pan} data is considered less reliable than using the FAO56-PM equation, E_{pan} data are widely available and may be useful for calculating average values of ET_o over several days (Ladson, 2008). If missing data results in a missing ET_o value for a particular day or several days in the SACSC output tables, daily E_{pan} data, which is displayed in the tables alongside daily ET_o, could be useful for estimating an average ET_o value. Hence the way in which E_{pan} data is measured and some of the potential problems with using it to estimate ET_o are discussed below.

Class "A" evaporation pans are used by the BoM to measure evaporation (in mm) for the 24-hour period to 9am each morning. The evaporation pans are circular, 120.7 cm in diameter and 25.5 cm deep. They are made of galvanized iron (22 gauge) and mounted on a wooden open frame platform that is 15 cm above ground level. The soil is built up to within 5 cm of the bottom of the pan. The pans are painted annually with aluminium paint and equipped with bird guards.

Since evaporation rate is largely dependent upon the temperature of the evaporating surface and the airflow over it, it is important to select a site where the airflow over the surface is representative of the mean airflow near the earth's surface for the region of interest (Canterford 1997). Areas where this airflow is either increased or reduced for any reason should be avoided, so attention to local obstructions is important.

The BoM requirements for the siting of evaporation pans are documented in Canterford (1997). These requirements include:

- The ground surface surrounding the pan must be relatively level and have the vegetative cover (trimmed to a few centimetres above the ground) comparable to that of the region;
- The pan must not be placed on concrete, rock, asphalt or other surfaces that may adversely affect the evaporation results;
- The distance of the pan from isolated obstructions which are higher than the top of the pan should be not less than ten times and preferably thirty times their height above the rim of the pan;
- And the pan is not closer than 1.5 m and preferably 2.5 m from any instrument higher than the pan.

Evaporation pans provide a measurement of the integrated effect of radiation, wind, temperature and humidity on evaporation from an open water surface (Allen et al. 1998). E_{pan} data are often used to estimate ET_o, for example for water resource planning and irrigation scheduling.

This study considered daily evaporation data from seven BoM weather stations in the Murray-Darling basin for the period January 1990 to March 2009 (n=7011 is the sample size at each site, assuming no missing data). The correlation between daily evaporation and daily ET_o was examined using a commercial spreadsheet package data analysis tool. In the SACSC output tables, daily ET_o for the period midnight to midnight is presented alongside daily evaporation for the 24-hour period to 9am. A correlation analysis using the data pairs presented in this manner found a strong positive correlation between daily evaporation and daily ET_o at all sites, as presented in Table III. However, more of the evaporation over the 24-hour period to 9am occurs on the day prior to that which the measurement is recorded beside. When daily evaporation data was offset by a day, so that daily ET_o and daily evaporation for the 24-hour period from 9am were paired, a correlation analysis using these data pairs found a stronger correlation, as shown in Table III.

Table III. Correlation between daily evaporation data and daily ET_o data.

Mildura Airport							
Variable	**Mean**	**SD**	**Variance**	**Sum**	**Min**	**Max**	**Range**
Evaporation	5.9	3.8	14.8	41232.9	0.0	22.0	22.0
ET_o	4.9	2.7	7.2	19623.8	0.5	14.2	13.7
Correlation	0.82						
Evap Offset Correlation	0.95						
Canberra Airport							
Variable	**Mean**	**SD**	**Variance**	**Sum**	**Min**	**Max**	**Range**
Evaporation	4.7	3.1	9.5	32968.2	0.0	19.8	19.8
ET_o	3.5	2.1	4.6	22274.3	0.4	12.6	12.2
Correlation	0.78						
Evap Offset Correlation	0.92						
Cobar Airport							
Variable	**Mean**	**SD**	**Variance**	**Sum**	**Min**	**Max**	**Range**
Evaporation	6.5	4.1	16.7	45769.8	0.0	24.0	24.0
ET_o	5.2	2.7	7.2	15086.3	0.5	14.7	14.2
Correlation	0.85						
Evap Offset Correlation	0.95						
Kyabram DPI							
Variable	**Mean**	**SD**	**Variance**	**Sum**	**Min**	**Max**	**Range**
Evaporation	4.4	3.2	10.2	27639.5	0.0	34.9	34.9
ET_o	3.6	2.5	6.4	2723.6	0.5	12.9	12.4
Correlation	0.80						
Evap Offset Correlation	0.86						
Loxton Research Centre							
Variable	**Mean**	**SD**	**Variance**	**Sum**	**Min**	**Max**	**Range**
Evaporation	5.3	3.4	11.5	37270.3	0.0	24.0	24.0
ET_o	4.4	2.5	6.1	18130.2	0.5	14.1	13.6
Correlation	0.82						
Evap Offset Correlation	0.96						
Moree Aero							
Variable	**Mean**	**SD**	**Variance**	**Sum**	**Min**	**Max**	**Range**
Evaporation	6.4	3.5	12.0	32370.5	0.0	19.8	19.8
ET_o	5.2	2.5	6.3	24577.2	0.5	14.8	14.3
Correlation	0.82						
Evap Offset Correlation	0.95						
Wagga Wagga AMO							
Variable	**Mean**	**SD**	**Variance**	**Sum**	**Min**	**Max**	**Range**
Evaporation	5.0	3.7	13.7	34932.9	0.0	22.0	22.0
ET_o	4.3	2.7	7.4	20805.6	0.4	15.3	14.9
Correlation	0.85						
Evap Offset Correlation	0.96						

These results are consistent with the results of Snyder et al. (2005), who noted that while there is a strong correlation between E_{pan} and ET_o, there are differences in energy fluxes and heat storage in evaporation pan water compared with soil covered with short vegetation.

Allen et al. (1998) observed that although evaporation pans respond in a similar fashion to the same climatic factors affecting crop transpiration, several factors produce significant differences in the loss of water from a water surface and from a cropped surface:

- Reflection of solar radiation from water in the shallow pan may be different from the assumed 23% for the grass reference surface;
- Storage of heat within the pan can be appreciable and may cause significant evaporation during the night, while most crops transpire only during the daytime. In addition, energy stored in the soil under a short crop canopy with a high canopy resistance to water vapour transfer will exhibit little night-time evaporation (Snyder et al. 2005);
- There are differences in turbulence, temperature and humidity of the air immediately above the respective surfaces;
- Heat transfer through the sides of the pan occurs and affects the energy balance.

In addition, the wire mesh of bird guards on BoM evaporation pans reduces the wind and radiation over the water's surface, thus reducing the evaporation rate. For Class A pans, this reduction has been estimated to be approximately 13% in a humid climate and 10% in a semi-arid climate (Linacre 1994).

The available literature on the subject provides much evidence that great care should be taken in using E_{pan} data to produce trustworthy ET_o values. Generally ET_o is estimated as the product of E_{pan} data and a pan coefficient K_p, i.e. $ET_o = K_p.E_{pan}$. In selecting the appropriate pan coefficient, the pan type, the ground cover at the station and its surroundings as well as the general wind and humidity conditions should be checked (Allen et al. 1998).

The siting of the pan and the pan environment influence the results, particularly when the pan is placed in a fallow rather than cropped field. Two cases are commonly considered: Case A where the pan is sited on a short green (grass) cover and surrounded by fallow soil; and Case B where the pan is sited on fallow soil and surrounded by a green crop. Depending on the size and state of the upwind buffer zone (fetch), pan coefficients will differ. The larger the upwind buffer zone, the more the air moving over the pan will be in equilibrium with the buffer zone. At equilibrium with a large fetch, the air contains more water vapour and less heat in Case A than in Case B. Pan coefficients for the Class A pan for different ground cover, fetch and climatic conditions are presented in Allen et al. (1998). Substantially lower values of K_p have been observed for dry, windy climates compared with humid, calm climates (Jensen et al. 1990).

Currently the BoM has no guidelines regarding specific distances between evaporation pans and the edges of crops or vegetation. This is a problem for estimating pan coefficients since ground cover and fetch are important inputs. Allen et al. (1998) recommended that the pan should be installed inside a short green cropped area of at least 15 by 15 m and that the pan should not be installed in the centre but at a distance of at least 10 m from the green crop edge in the general upwind direction.

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GLOSSARY

Albedo – The proportion of solar energy incident on a surface that is reflected (Ladson, 2008).

Julian day - The number of the day in the year between 1 (January 1st) and 365 or 366 (December 31st).

Solar declination – The latitude at which the sun is directly overhead (Ladson, 2008).

Specific heat of air at constant pressure – The specific heat of air at constant pressure, c_p, is the amount of energy required to increase the temperature of moist air by 1 ^oC.