Back to the basics of understanding ET

W. JAMES SHUTTLEWORTH
Department of Hydrology & Water Resources, University of Arizona, Tucson, Arizona 8721, USA
jshuttle@hwr.arizona.edu

Abstract Hydrocomplexity occurs when hydrologists realize that improved theoretical description of a hydrological process requires the representation of controlling features that hitherto had not been considered necessary. This paper makes a critical reappraisal of currently recommended methods for estimating the water requirements of irrigated crops, which reveals there is a fundamental theoretical inconsistency between present day understanding of the interaction between plant canopies and the atmosphere as represented by the Penman-Monteith (P-M) equation, and the procedures for estimating plant water requirements currently recommended by FAO. In the P-M equation, stomatal and aerodynamic controls on the transfer processes are expressed in terms of resistances which are embedded among the meteorological controls with crop-to-crop differences expressed in terms of different values for these resistances. However, the current procedure recommended by FAO for estimating crop water represents crop-to-crop differences as a simple multiplicative crop factor applied to an estimated evaporation rate calculated by the P-M equation for a *single* reference crop with fixed surface resistance and aerodynamic characteristics. Recent theoretical developments that allow adoption of the more robust P-M equation description of ET for *all* irrigated crops are reviewed along with an example application of this new approach to estimate the water requirements in the major irrigation districts of Australia. Broader adoption into irrigation practice of this method, which is known as the Matt Shuttleworth approach, is recommended on the grounds that it is consistent with present-day understanding of the evaporation process, is feasible and simple to apply, and will facilitate future adoption of realistic representations of the effect on evapotranspiration of plant stress and of crops with partial ground cover. However, when not all the weather variables needed to calculate crop evaporation rates are available, an estimate of reference crop evaporation may still have to be made by scaling down the measured evaporation loss from an evaporation pan by a "pan factor". In the past the value of this pan factor has been defined empirically but recent research into the physics which controls evaporation from the Class A evaporation pan has resulted in a physically-based equation that describes pan evaporation in terms of ambient climate variables. This equation, which has been verified experimentally, allows a formal definition of the pan factor that is used to investigate theoretically how ancillary measurements (or estimates) of temperature and wind speed at an evaporation pan site might be used to improve the accuracy of a pan-based estimate of reference crop evaporation.

Key words crop evaporation; pan evaporation; evapotranspiration; crop water requirements

1 INTRODUCTION

The theme of this Xth Kovacs Colloquium is: *Hydrocomplexity: New Tools for Solving Wicked Water Problems*. Hydrocomplexity occurs when hydrologists realize that improved theoretical description of a hydrological process or phenomenon requires the representation of controlling features that hitherto had not been considered necessary. Such recognition may arise because the theoretical description has been proven not to be universally adequate on the basis of observations, or because research suggests that an alternative, more fundamental understanding of the process or phenomenon is appropriate. In the latter case, introducing such fundamental understanding is likely to result in a representation that is more resilient when applied in different geographical or climate conditions. The definition for the word "wicked" is broad, ranging from "morally bad in principle or practice", through "highly offensive; arousing aversion or disgust", to "naughtily or annoyingly playful". Whether the fact that a water-related problem requires a more complex description than hitherto considered necessary means that it is "wicked" is a matter of opinion. In the present age many hydrologists have direct or indirect access to computational resources by means of which complex equations can be quickly evaluated. Consequently numerical simplicity during implementation is of less importance than previously, and more complete and resilient descriptions are increasingly preferred, even if they are theoretically more complex. The present paper overviews recent research in the area of evapotranspiration and, on this basis, argues for the use of the resulting understanding in the practical application of estimating the water requirements of irrigated crops.

Early research showed evaporation from terrestrial surfaces is primarily meteorologically determined when water is not limited and this led to the hypothetical concept of “potential” rates of evaporation estimated from weather data. Penman (1948) formulated the basic physics of evaporation using two terms, an energy term related to radiation and an aerodynamic term related to the vapour pressure deficit of the air and wind speed. He suggested evaporation from well-watered grass and moist bare soil might be related to that from open water using multiplicative factors. By the mid 1970s this, by then long-established, way of thinking determined the United Nations Food and Agriculture Organization’s (FAO) recommended method for estimating the water requirements for irrigated crops (Doorenbos & Pruitt, 1977). FAO defined reference crop evapotranspiration, ET_0, for short green grass plentifully supplied with water estimated (at that time) by one of several alternative equations depending on available weather data. Evapotranspiration from any other well-watered crop, ET_c, was then assumed to be calculated using a crop specific coefficient, K_c, thus:

$$ET_c = K_c ET_0 \tag{1}$$

FAO provided a table of K_c values for a range of well-watered crops, the values of which were (it is assumed) derived from field studies where the well-watered crop evapotranspiration rate, ET_c and the weather variables needed to calculate ET_0 were measured so that K_c could be derived. Many years of application followed.

However, the agricultural community’s adoption of FAO’s recommendation omitted recognition of important subsequent advances in the specification of evapotranspiration. Monteith generalized Penman’s original approach and derived the Penman-Monteith equation (Monteith, 1965), hereafter referred to as the P-M equation. The P-M equation calculates ET_c using a surface resistance, r_s, and an aerodynamic resistance, r_a, from:

$$ET_c = \frac{\Delta A + (\rho c_p D)/r_a}{\Delta + \gamma[1 + r_s/r_a]} \tag{2}$$

where Δ is the rate of change of saturated vapour pressure with temperature, A is the energy available for evapotranspiration at the evaporating surface (often called the available energy); D is the vapour-pressure deficit (VPD) measured at the “screen height” above the crop from which level r_a is defined; γ is the psychrometric constant, ρ is the density of air, and c_p is the specific heat of air at constant pressure. The P-M equation is a general description of evapotranspiration that applies to all vegetated surfaces (including those that are water stressed) and has become widely adopted by the hydrological and meteorological communities.

Notwithstanding the publication and widespread adoption of the P-M equation, agriculturalists continued to use the original “two-step” approach as recommended by FAO. But there was increasing evidence that the approach may be problematic when K_c values derived in one place were used for the same crop in another place. Wallace (1995), for example, demonstrated that crop factors are inherently a complex mixture of both the physiology of the crop they represent and the climate within which K_c values are derived and/or used. Recognizing the greater realism of the P-M equation, FAO subsequently modified their guidelines (Allen *et al.*, 1998; hereafter referred as FAO-56) by adopting the P-M equation to calculate reference crop evapotranspiration (ET_0). However, FAO’s recommendations still retained the two-step approach because it is still necessary to multiply ET_0 by a crop factor to obtain ET_c.

The reluctance of the agricultural irrigation community to change practice may in part be due to the limited availability of values of aerodynamic resistance and surface resistance for non-stressed, well watered irrigated crops other than the reference crop. Shuttleworth (2006) addressed this need by combining modern thinking in surface energy exchange and boundary layer meteorology to derive a means for: (i) specifying aerodynamic resistance of any crop from readily available 2-m climate station data; and (ii) converting existing K_c values to their equivalent surface resistance. The resulting “one-step” method is called the Matt-Shuttleworth (M-S) approach. Shuttleworth & Wallace (2009) then applied the M-S approach in the context of irrigated crops in Australia and better defined the procedure for converting existing values of K_c into their equivalent values of r_s. One purpose of this paper is to overview the derivation and application of this new and more theoretically robust approach for estimating the water requirements of irrigated crops.

When not all the weather variables needed to calculate crop evaporation rates are available, an estimate of reference crop evaporation may still have to be made by scaling down the measured evaporation loss from an evaporation pan using a "pan factor". Recent investigation (Rotstayn *et al*., 2006) has resulted in better understanding of the evaporation rate from evaporation pans that, for the first time, allows formal definition of the pan factor. This in turn allows study of variations in the value of the pan factor with ambient conditions. It also allows investigation of the extent to which the presence of any ancillary data available at the evaporation pan site (in the form of measured radiation, and/or wind speed, and/or temperature) can be used to improve the accuracy of a pan-based estimate of reference crop evaporation. Undertaking such an investigation is the second purpose of this paper.

2 THEORETICAL OVERVIEW

2.1 Specifying atmospheric aridity

When using the P-M equation to estimate crop water requirements it has become common practice (FAO-56; Pereira *et al.*, 1999; Shuttleworth, 2006) to calculate the aerodynamic resistance between a vegetation-covered surface and a level, z, above the surface using the equation:

$$r_a = \frac{\ln[(z-d)/z_0]\,[\ln[(z-d)/(z_0/10)]}{k^2 u_Z} \tag{3}$$

where u_Z is the wind speed at the height z, k is the von Karman constant (= 0.41), and d and z_0 are the zero plane displacement and roughness length of the vegetated surface, respectively. FAO-56 specifies the crop height, h_{rc}, for a reference crop as 0.12 m and assumes $z_0 = 0.123h_{rc}$ and $d = 0.67h_{rc}$. Using these values in equation (3) with wind speed measured at 2 m gives the aerodynamic resistance to 2 m for a reference crop as $(r_a)_{rc} = 208/u_2$. FAO-56 also specified a fixed value of 70 s m^{-1} for the surface resistance of the reference crop.

Based on the earlier work of Penman (1948, 1963), Priestley & Taylor (1972) proposed that the expression:

$$ET_{PT} = \alpha \frac{\Delta A}{\Delta + \gamma} \tag{4}$$

provided an "appropriate framework" for apportioning surface energy between sensible heat and evapotranspiration, and reached "the tentative conclusion that α is about 1.26 for saturated surfaces". Equation (4) with α set equal to 1.26 has sometimes since been used to provide an estimate of reference-crop evapotranspiration in humid conditions (Doorenbos & Pruitt, 1977; Shuttleworth, 1993). By equating ET_{PT} with ET_0 calculated from equation (2) using r_a and r_s appropriate for reference crop evapotranspiration, Shuttleworth (2006) specified the relationship between vapour-pressure deficit measured at 2 m and available energy that characterizes the humidity condition of the atmosphere in terms of the value of the climatological resistance, r_{clim}, defined by the equation:

$$r_{\text{clim}} = (\rho c_p D)/(\Delta A) \tag{5}$$

Substituting the aerodynamic and surface resistances for the reference crop into equation (2), then equating ET_c to ET_{PT} from equation (4) and re-arranging, gives the climatological resistance as:

$$r_{\text{clim}} = \frac{208}{u_2}\left(\frac{\alpha[\Delta + \gamma(1 + 0.377u_2)]}{\Delta + \gamma} - 1\right) \tag{6}$$

When atmospheric humidity conditions are specified in this way the hitherto imprecise concept of a "humid atmospheric condition" becomes well defined through the value of r_{clim} calculated from equation (6) as a function of wind speed and temperature (because Δ is a function of temperature) with α = 1.26. It is also helpful to define a value of climatological resistance typical of "arid atmospheric conditions". Jensen *et al.* (1990) propose α = 1.74 as the value of α required for ET_0 to equal ET_{PT} in arid conditions. Adopting this value for α in equation (6), it is again possible to specify an arid atmosphere in terms of r_{clim}. For the example case with wind speed 2 m s^{-1} and temperature 15°C, r_{clim} = 60 s m^{-1} and 123 s m^{-1} in humid and arid conditions, respectively.

2.2 The Matt-Shuttleworth approach

The Matt-Shuttleworth approach involves the general application of the P-M equation to estimate the rate of evaporation loss from *all* well watered crops, not just the reference crop. To allow this, it is necessary to define how standard weather variables measured (it is assumed) at 2 m above short grass can be used to calculate evaporation from crops with different heights, some of which may have a crop height greater than 2 m. To resolve this issue Shuttleworth (2006) defined a version of the P-M equation that is indexed to a hypothetical common "blending height" arbitrarily selected to be at 50 m, so that the reference height and value of VPD become the same when calculating both well-watered crop and reference crop evapotranspiration rates. The reader is recommended to read Shuttleworth (2006) for details of the assumptions used and the derivation of this equation, which takes the final form:

$$ET_c = \frac{\Delta A_c + \left(\frac{D_{50}}{D_2}\right)\frac{\rho c_p u_2 D_2}{R_c^{50}}}{\Delta + \gamma\left(1 + \frac{(r_s)_c u_2}{R_c^{50}}\right)} \tag{7}$$

where A_c is the available energy for the crop, D_{50} and D_2 are the VPD at 50 m and 2 m, respectively, $(r_s)_c$ is the surface resistance of the crop, and R_c^{50} is an aerodynamic coefficient that allows calculation of aerodynamic resistance from 2-m wind speed for a crop with height h_c. The formulae needed to calculate (D_{50}/D_2) from weather variables measured at 2 m over a reference crop and R_c^{50} from the height of the crop are given in the Appendix. Although these two formulae appear complex, in practice they can be easily coded in computer programs and could also be provided in tabular form if required. Equation (7) provides the value of daily average latent heat flux in W m^{-2}. To enhance familiarity among practitioners, this equation can be rewritten in terms of daily total evaporated water in mm d^{-1}, i.e. analogous to the equation for reference crop evaporation given by FAO-56. When re-expressed in these units the equation takes the form:

$$ET_c^{(mm)} = \left(\frac{\Delta}{\Delta + \gamma^{**}}\right)A_c^{(mm)} + \left(\frac{\Delta}{\Delta + \gamma^{**}}\right)\left(\frac{D_{50}}{D_2}\right)\left(\frac{187219}{T_2 + 275}\right)\frac{u_2 D_2}{R_c^{50}} \tag{8}$$

where the superscript (mm) implies values are converted to equivalent mass of evaporated water, and γ^{**} is a "re-modified" psychrometric constant, given by:

$$\gamma^{**} = \gamma\left(1 + \frac{(r_s)_c u_2}{R_c^{50}}\right) \tag{9}$$

Equation (7) can be applied both to a general crop with surface resistance $(r_s)_c$, and to the reference crop with $(r_s)_c$ = 70 s m^{-1} and aerodynamic resistance equal to $302/u_2$ (this being the aerodynamic resistance to 50 m for a crop height of 0.12 m). If the resulting estimated evaporation rates calculated from the two P-M equations are introduced into equation (1), after re-arrangement it follows that:

$$K_c = \left(\frac{\frac{R_c^{50}}{u_2} + \frac{D_{50}}{D_2} r_{\text{clim}}}{\frac{302}{u_2} + \frac{D_{50}}{D_2} r_{\text{clim}}} \right) \left(\frac{(\Delta + \gamma)\frac{302}{u_2} + 70\gamma}{(\Delta + \gamma)\frac{R_c^{50}}{u_2} + \gamma (r_s)_c} \right) \quad (10)$$

Equation (10) clearly shows that ambient weather changes the value of the crop coefficient via the values of r_{clim} and wind speed. Figure 1 shows, for example, that there are substantial variations in the crop factor: (a) with wind speed and crop height for a fixed value of surface resistance; (b) with wind speed for a range of surface resistances but a fixed crop height, (c) with temperature for a range of surface resistances but fixed crop height and wind speed; and (d) with available energy for a range of surface resistances with fixed crop height and wind speed. The presence of such variations is a major motivation for seeking to estimate well-watered crop evapotranspiration from surface and aerodynamic resistances using the P-M equation rather than using crop factors.

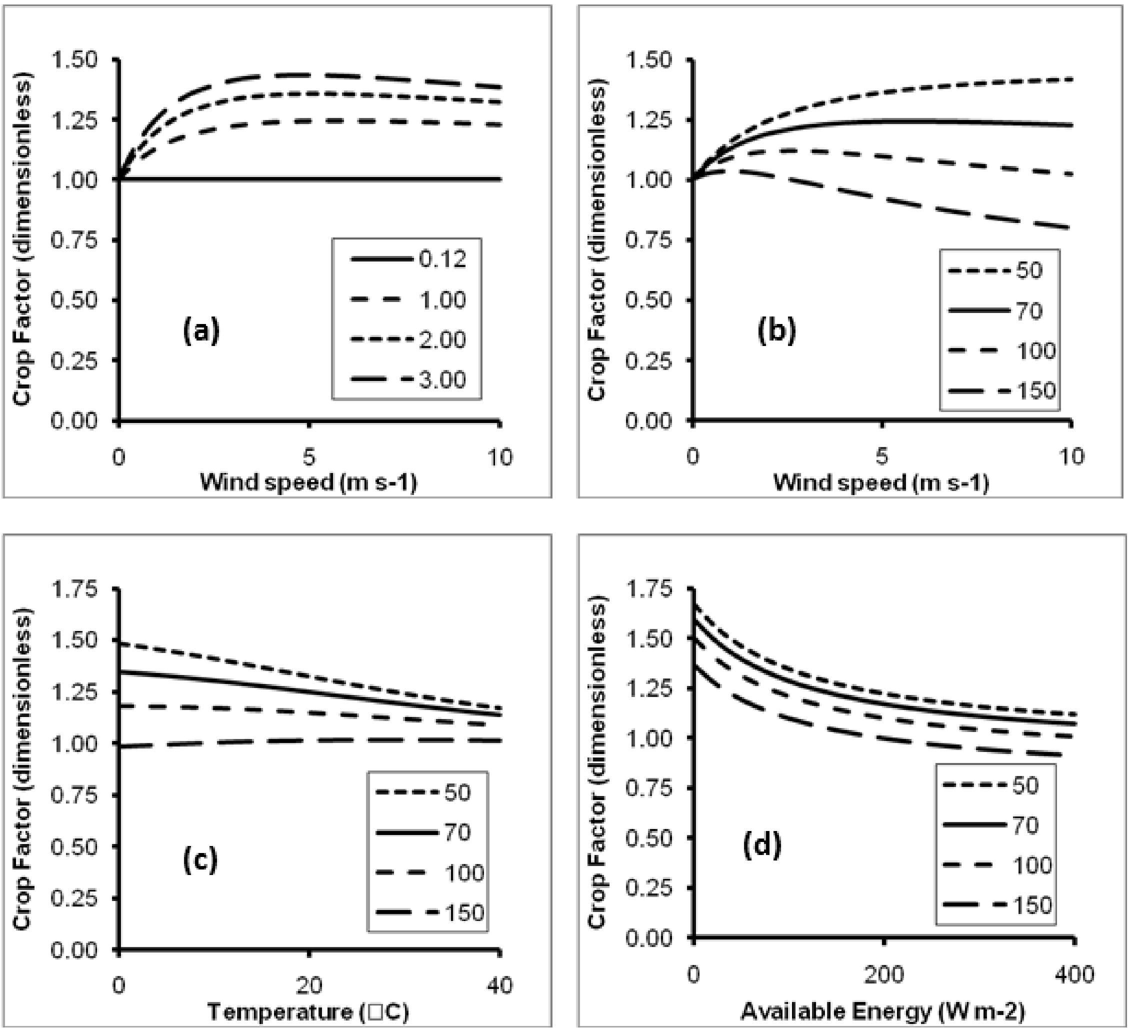


Fig. 1 Crop factors calculated from equation (10) unless otherwise stated with a temperature of 29.7°C, vapour pressure deficit of 2.54 kPa, and available energy 174 W m^{-2}, these being selected by Shuttleworth & Wallace (2009) as typical of prevailing conditions during full cover cotton crop growth at Narrabri, Australia. Variations are shown: (a) with available energy for surface resistances of 50, 70, 100, and 150 s m^{-1} with a fixed crop height of 1 m and wind speed of 2 m s^{-1}; (b) with wind speed for crop heights of 0.12, 1, 2 and 3 m assuming a fixed surface resistance of 70 s m^{-1}; (c) with wind speed for surface resistances of 50, 70, 100, and 150 s m^{-1} with a fixed crop height of 1 m; and (d) with temperature for surface resistances of 50, 70, 100, and 150 s m^{-1} with a fixed crop height of 1 m and wind speed of 2 m s^{-1} .

Shuttleworth (2006) also describes how the effective value of unstressed surface resistance can be estimated from the values of crop factor K_c^{FAO} given by FAO-56 using the equation:

$$(r_s)_c = \frac{r_s^1}{K_c^{FAO}} - r_s^2 \qquad (11)$$

The assumptions made in deriving equation (11) are summarized in the Appendix along with the formulae that calculate r_s^1 and r_s^2. To evaluate $(r_s)_c$ it is necessary to know (or to assume) a value for a so-called "preferred" temperature, T^{pref}, this being the temperature when the value of K_c^{FAO} was originally calibrated. In practice knowledge of T^{pref} is rarely available because FAO does not reference the original individual calibration sources they used to define K_c^{FAO}. Fortunately Shuttleworth & Wallace (2009) show that for many important irrigated crops the relationship between $(r_s)_c$ and K_c^{FAO} has limited sensitivity to the assumed value of T^{pref} and they recommend that in the absence of better information, T^{pref} should be set to a mid range temperature of 20°C. Table 1 gives example values of $(r_s)_c$ calculated from equivalent mid season values of K_c^{FAO} with T^{pref} = 20°C.

Table 1 Values of surface resistance for selected irrigated crops (including the reference crop) calculated using equation (11) and associated equations from values of K_c^{FAO} and maximum crop height taken from Table 12 of FAO-56 with T^{pref} = 20°C.

Irrigated crop	Assumed value of K_c (dimensionless)	Assumed crop height (m)	Suggested surface resistance (s m^{-1})
Reference crop	**1.00**	**0.12**	**70**
Alfalfa (average)	0.95	0.70	127
Bermuda	1.00	0.35	92
Clover (average)	0.90	0.60	149
Rye (average)	1.05	0.30	66
Pasture (rotation)	0.95	0.23	109
Pasture (extensive)	0.75	0.10	254
Small vegetables	1.05	0.38	72
Solanum family	1.15	0.70	50
Cucurbitaceae	1.00	0.34	91
Roots & tubers	1.10	0.68	66
Legumes	1.15	0.55	44
Cereals	1.15	1.00	60
Cotton	1.18	1.35	60
Maize (grain)	1.20	2.00	64
Sorgum (grain)	1.05	1.50	100
Rice	1.20	1.00	46
Millet	1.00	1.50	118
Sugar cane	1.25	3.00	63
Cacao	1.05	3.00	113
Coffee	0.95	2.50	143
Tea	1.00	1.50	118
Grape (table)	0.85	2.00	184
Grape (wine)	0.70	1.75	273
Almonds	0.90	5.00	169
Avocado	0.85	3.00	186
Citrus (50% canopy)	0.60	3.00	345
Kiwi	1.05	3.00	113
Walnut	1.10	4.50	106
Olives	0.70	4.00	265

2.3 Formal definition of pan factor

In the past the value of the pan factor has been defined empirically by comparing reference crop evaporation rate, λE_{rc}, with measured pan evaporation rate, λE_{pan}, at one location and in one climate, and then applying this ratio elsewhere. On this basis approximate values of pan factor were tabulated in different weather conditions (e.g. Doorenbos & Pruitt, 1977; Shuttleworth, 1993), but such tabulation was made without proper theoretical understanding of the origins of such variations.

In recent years there has been research into the physics which controls evaporation from the Class A evaporation pan. Rotstayn *et al*. (2006) developed the "Penpan" equation which is based on the work of Thom *et al*. (1981) and Linacre (1994), and which is a physically-based description of pan evaporation in terms of ambient climate variables. The Penpan equation is an implementation of the P-M equation (i.e. equation (2)) in which the effective aerodynamic resistance for a Class A evaporation pan is prescribed to be:

$$(r_a)_{pan} = \frac{C_{pan}}{1 + 1.35u_2} \tag{12}$$

with the average value of C_{pan} set to 224, and the effective surface resistance for a Class A evaporation pan prescribed to be given by:

$$(r_s)_{pan} = 1.4(r_a)_{pan} \tag{13}$$

Roderick *et al.* (2007) experimentally verified the Penman equation against Class A pan data from pan sites in Australia where the measured meteorological variables required in the equation were also available. They showed that *on average*, the Penpan equation gave a reasonable description of monthly-average measured pan evaporation rate, see Fig. 2. However, it should be noted that in Fig. 2 there are systematic site-to-site discrepancies in the order of 10–20% between measured pan evaporation and the value estimated by the Penpan equation when C_{pan} is set to the value 224. These discrepancies are significant in the context of the present analysis as discussed later.

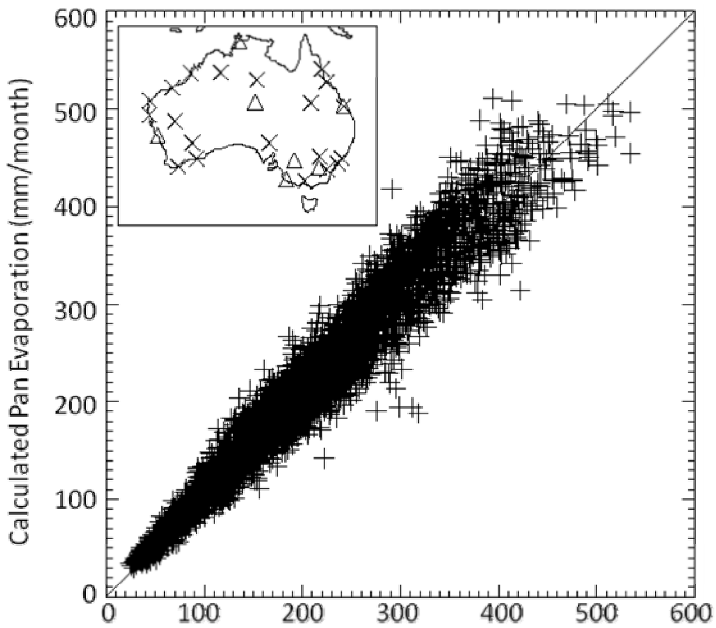


Fig. 2 Comparison between observed monthly average Class A pan evaporation for the Australian pan sites shown in the insert *versus* calculated pan evaporation rate given by the Penpan equation using data at these sites (redrawn from Figure 1 of Roderick *et al*., 2007).

The Penpan equation and FAO's recommended equation for calculating reference crop are both implementations of the P-M equation with different values of surface and aerodynamic resistance, i.e. $(r_s)_{rc}$ = 70 and $(r_a)_{rc} = 208/u_2$ for a reference crop, and $(r_s)_{pan} = 1.4(r_a)_{pan}$ and $(r_a)_{pan} = C_{pan}/(1+ 1.35u_2)$ for a pan, respectively. By substituting these pairs of values into equation (1) and taking the ratio of the two calculated rates, it follows that:

$$K_p = \frac{[(r_a)_{rc} + r_{c\lim}]}{[(A_{pan}/A_{rc})(r_a)_{pan} + r_{c\lim}]} \frac{(\Delta + 2.4\gamma)(r_a)_{pan}}{(\Delta(r_a)_{rc} + \gamma[(r_a)_{rc} + (r_s)_{rc}]} \quad (14)$$

where A_{rc} and A_{pan} are the energy available for evaporation for a reference crop and an evaporation pan, respectively. In this analysis it is assumed that available energy can be equated to net radiation, and that:

$$A_{rc} = (1 - a_{rc})S + L_n \quad (15)$$

and:

$$A_{pan} = (1 - a_{pan})S + L_n \quad (16)$$

where S is the incoming solar radiation, L_n is the net longwave radiation exchange (assumed independent of the surface), a_{veg} = 0.23 for a reference crop and, following Rotstayn *et al*. (2006), a_{pan} = 0.14 for a Class A evaporation pan. Equations (14), (15) and (16) are used to explore the sensitivity of K_p to ambient meteorological conditions below. They can also be used to explore what benefit can be derived from using ancillary measurements (or estimates) of the meteorological variables required in equation (14) when some (but not all) the weather variables needed to calculate reference crop evaporation directly are measured at a pan site.

3 RESULTS

3.1 Comparison of the Matt-Shuttleworth and FAO approaches

Shuttleworth & Wallace (2009) compared estimates of crop water requirements made using the M-S approach and the traditional FAO approach using 10-year daily average data from climate stations at five locations in important irrigation districts in Australia. The locations considered were in the Burdekin delta in Queensland, the Harvey River region in Western Australia, the Murrumbidge and Narrabri areas in New South Wales, the Ord basin in the north of Western Australia.

Figure 3(a)–(c) shows measured climatological resistance (i.e. calculated from equation (5)) at the coastal (humid) Burdekin site, the continental (semi-arid) Narrabri site, and northern (extremely semi-arid) Ord site. Also shown are the values of climatological resistance in humid conditions calculated from equation (6) with α = 1.26. These figures reveal that the prevailing climate is humid only in certain months at the Burdekin site but is never fully humid at the other two sites. The prevailing climate becomes progressively more arid from the Burdekin, to the Narrabri, to the Ord sites. Figure 3(d)–(f) shows the cumulative evaporation during the growing season for a short well-watered cotton crop hypothetically growing at these same three sites, while Figure 3(g)–(i) shows the cumulative evaporation during the growing season for a taller sugar cane crop hypothetically growing at these sites. Figure 3 as a whole clearly shows that when estimating crop water requirement using the M-S approach rather than the FAO approach, the change is more significant for taller crops and for crops growing in more arid climates. This is to be expected because the M-S approach makes a better estimate of the aerodynamic influence on evaporation rate for different crops than the FAO approach: the latter only allows for the aerodynamic influence on the evaporation rate for a short grassland crop.

Figure 4 shows example results of a numerical comparison between the calculated cumulative evaporation given using the Matt-Shuttleworth approach at the five Australian sites relative to that calculated using the traditional FAO approach for a sugar cane crop during each stage in the growth season and for the season as a whole. Similar calculations can be made for other crops and,

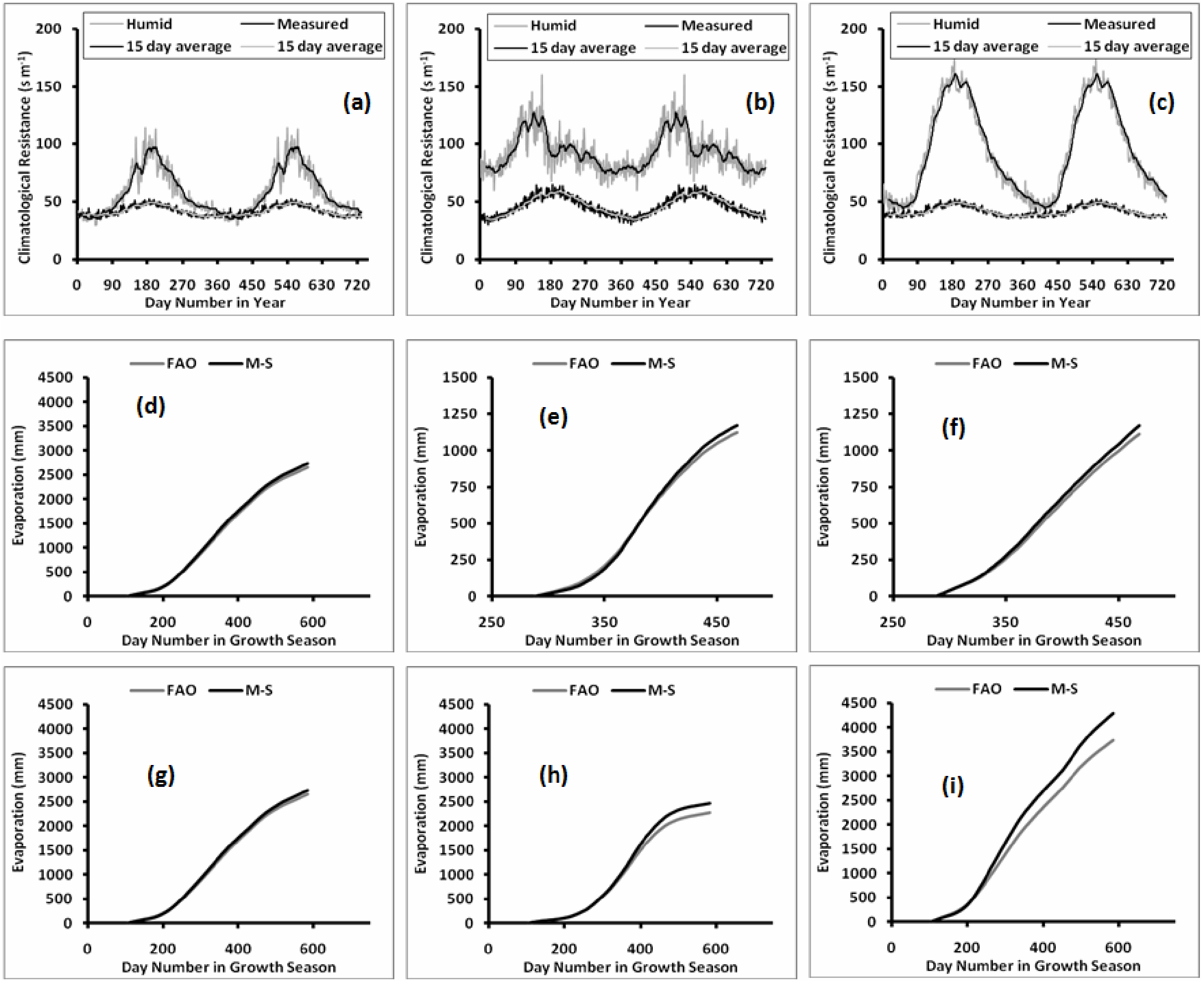
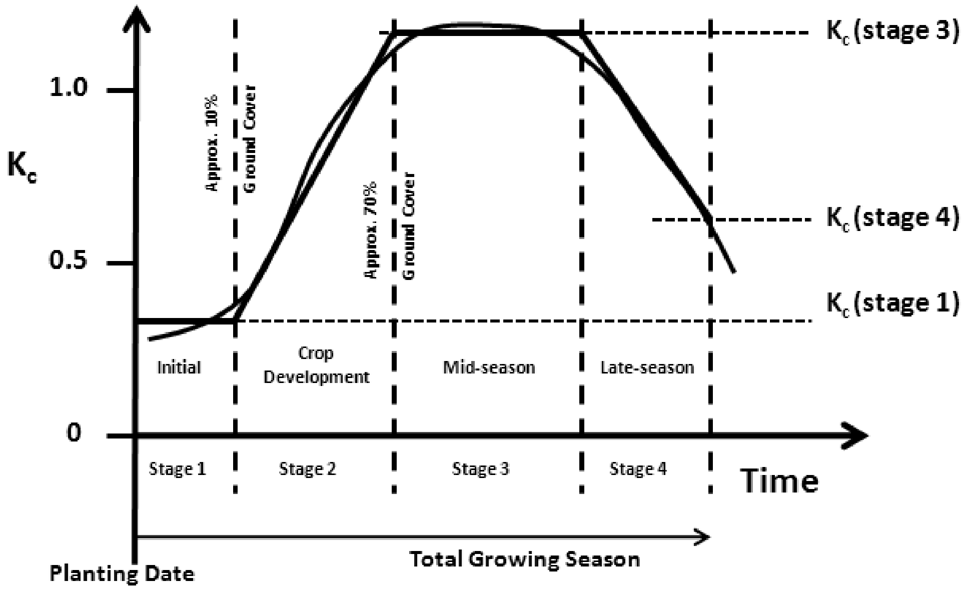


Fig. 3 (a), (b) and (c) show measured climatological resistance (equation (5)) and the value of climatological resistance in humid conditions (equation (6) with α = 1.26) over two annual cycles. (d), (e) and (f) show cummulative evaporation from a cotton crop over a growth cycle; and (g), (h) and (i) the cumulative evaporation from a sugar cane crop over a growth cycle. (a), (d) and (g) are calculated from data at the (humid) coastal Burdekin site; (b), (e) and (h) are from data from the (semi-arid) continental Narrabri site; and (c), (f) and (i) are from data at the (more extreme semi-arid) Ord site.



Percentage Difference of M-S Relative to FAO Calculated Evaporation					
Site	Stage 1	Stage 2	Stage 3	Stage 4	All Season
Burdekin	-13%	3%	3%	4%	3%
Narrabri	-2%	-4%	10%	8%	8%
Griffith	-27%	-8%	16%	9%	12%
Harvey	1%	6%	3%	12%	5%
Ord	-13%	13%	15%	19%	15%

Fig. 4 Schematic diagram of the seasonal evolution in the FAO crop factor, K_c^{FAO}, and percentage difference in the calculated cumulative evaporation from a sugar cane crop given using the Matt-Shuttleworth approach at five Australian sites relative to that calculated using the traditional FAO approach during each stage in the growth season and for the season as a whole.

in general, the Shuttleworth & Wallace (2009) study reports that in the typically arid and windy climate of Australian irrigation districts, using the M-S approach gives estimates of evapotranspiration for well-watered crops that can differ from the FAO estimates by several tens of percent in individual growth phases, depending on location and stage. For the whole growth season, M-S evapotranspiration estimates are 4–18% higher than when using the FAO method for sugar cane and ~5% higher for a (shorter) cotton crop. The difference when estimating well-watered pasture evapotranspiration is smaller (0.5–2.5%). Shuttleworth & Wallace conclude by recommending adoption of the M-S approach into irrigation practice on the grounds that this is consistent with present day understanding of the evaporation process, is feasible and simple to apply, and will facilitate future adoption of realistic representations of the effect on evapotranspiration of plant stress and of crops with partial ground cover.

3.2 Use of the formal definition of pan factor

Sensitivity of pan factor to ambient conditions The analytic expression for pan factor, i.e. equation (14), contains the ratio (A_{pan}/A_{rc}) and it is of interest to explore the extent to which changes in the value of this ratio influences the value of K_p. Combining equations (15) and (16), it can be easily shown that:

$$\frac{A_{pan}}{A_{rc}} = A_{rc}^{-1}\left[\frac{A_{rc} - L_n)(1 - a_{pan})}{(1 - a_{rc})}\right] + L_n \tag{17}$$

Figure 5 gives the value of (A_{pan} /A_{rc}) for values of reference crop available energy of between 100 and 500 W m^{-2} and for net longwave radiation values of 0, –50, and –100 W m^{-2}. For the majority of likely conditions, (A_{pan}/A_{rc}) is within the range 1.1 to 1.2.

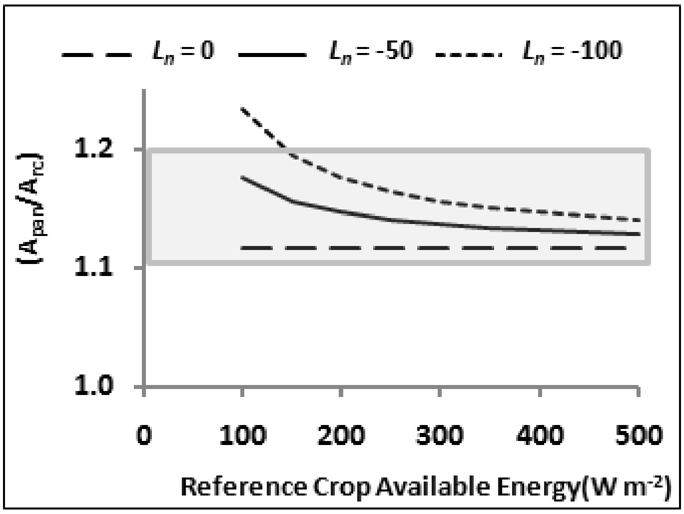


Fig. 5 Variation in the ratio (A_{pan}/A_{rc}) calculated by equation (17) as a function of the energy available to the reference crop calculated for net longwave radiation values 0, –50, and –100 W m^{-2}.

Figure 6 shows the variation in K_p as a function of wind speed for three values of (A_{pan}/A_{rc}) = 1.1, 1.5, and 1.2, calculated at 10, 20, and 30°C and in both humid and arid conditions, with the value of r_{clim} required in equation (14) calculated from equation (6) with α = 1.26 and α = 1.74, respectively. It is apparent in Fig. 6 that, although the effects of different fractional net longwave radiation contributions to the available energy are noticeable, their influence on the value of K_p is limited, being least (about ±1%) at higher wind speeds in arid conditions and greatest (about ±3%) at lower wind speeds in humid conditions.

Figure 7 shows the variation in K_p as a function of wind speed calculated at 10, 20, and 30°C in humid and arid conditions with (A_{pan}/A_{rc}) set to the mid-range value 1.15. This figure demonstrates that temperature can affect K_p in both humid and arid conditions and gives differences of ±12% at both low (0.5 m s^{-1}) and high (8 m s^{-1}) wind speed. The value of K_p is greater at higher temperatures when wind speed is low, and *vice versa*. However at intermediate wind speeds the effect of temperature on the calculated value of K_p is small. On the other hand, the effect of wind speed on pan coefficient is always large, giving a reduction by a factor of about 1.5 as wind speed increases from 0.5 to 8 m s^{-1}, depending on conditions. Together these results indicate that knowledge of wind speed is always likely to be helpful when defining the pan coefficient needed to estimate reference crop evaporation from pan evaporation, but that poor knowledge of (A_{pan}/A_{rc}) has much less impact. Poor knowledge of temperature also has less impact except at very high or very low wind speed when it can alter K_p by around 10%.

The influence of ancillary climate data If not all the meteorological variables needed to calculate reference crop evaporation are available but pan evaporation data are available, the required value of K_p must be calculated from equation (14) by first specifying whether the

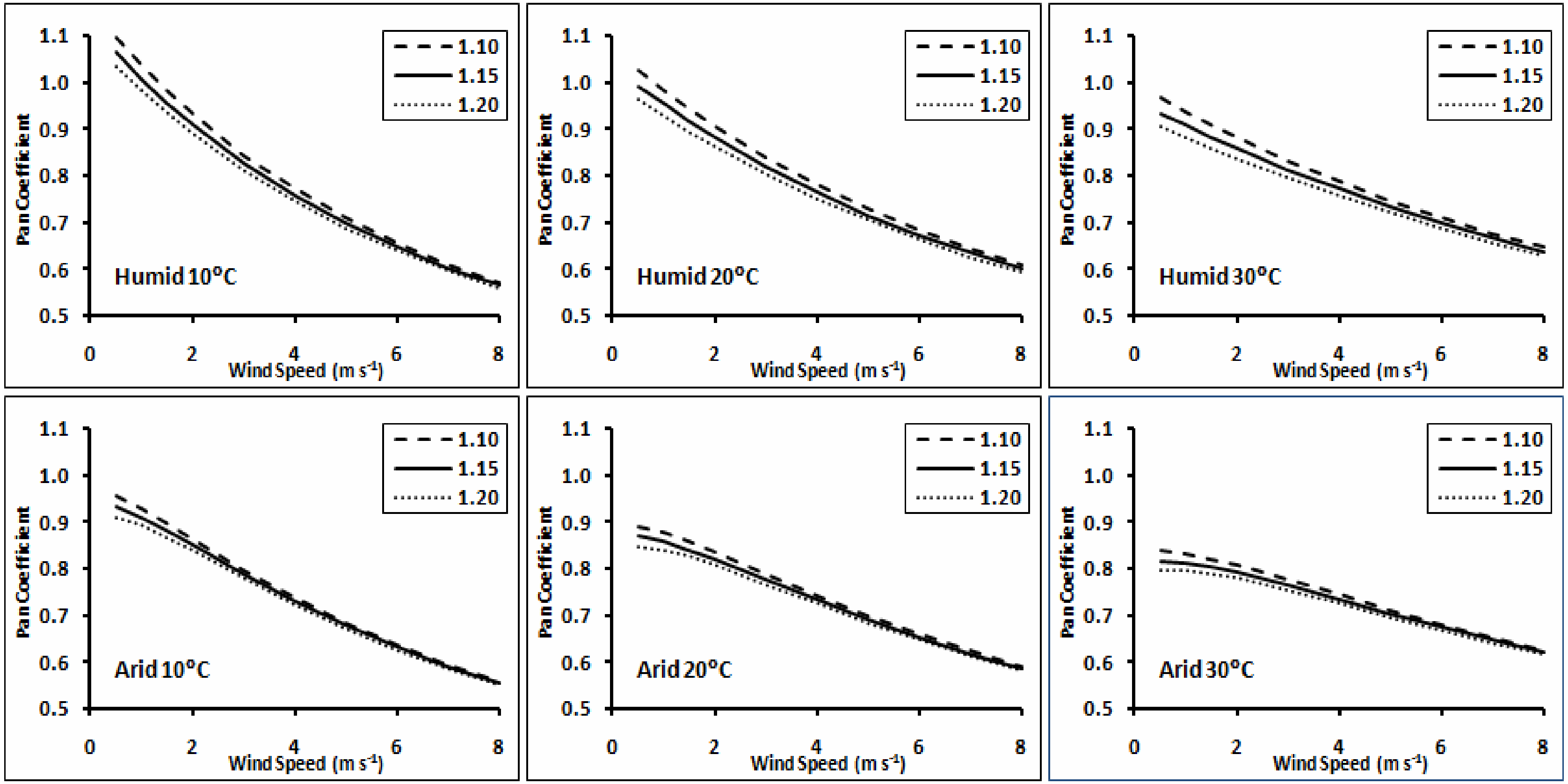


Fig. 6 Variation in K_p as a function of wind speed for (A_{pan} /A_{rc}) = 1.1, 1.15, and 1.2 calculated at 10, 20, and 30°C (vertical columns of figures), in both humid and arid conditions (horizontal rows of figures) with the value of r_{clim} calculated from equation (6) with α = 1.26 and α = 1.74, respectively.

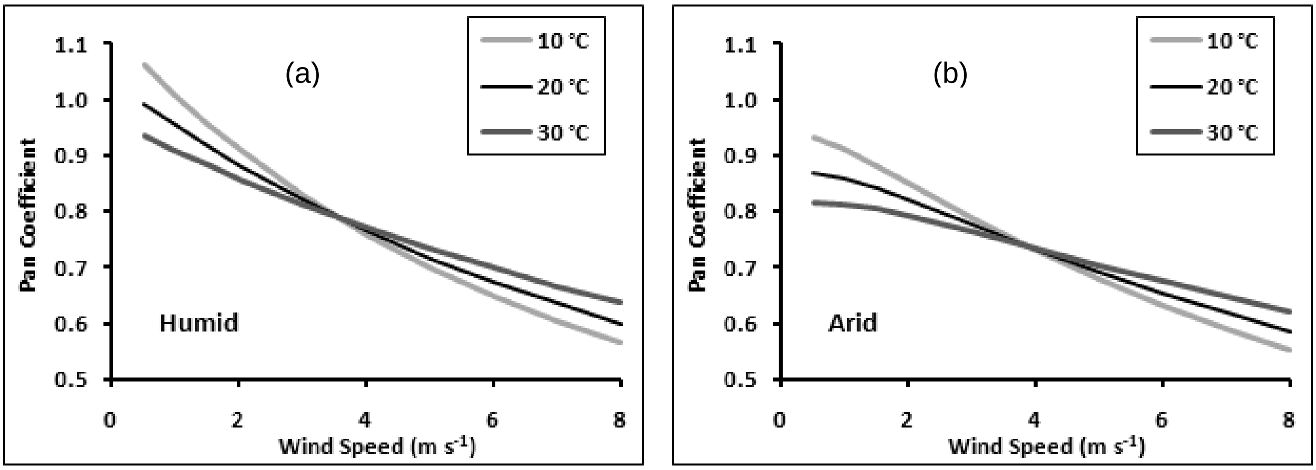


Fig. 7 Variation in K_p as a function of wind speed with (A_{pan}/A_{rc}) set to 1.15 calculated at 10, 20, and 30°C in humid conditions (a) and arid conditions (b).

atmospheric conditions are to be considered humid or arid, and then ascribing values to the missing measurement(s) of (A_{pan}/A_{rc}), temperature and wind speed. "Default" values of these three variables are therefore required for use in such situations. In the case of (A_{pan}/A_{rc}), the analysis above suggests that using the value 1.15 gives estimates of K_p accurate to within a few percent. This is fortunate because poor knowledge of shortwave and longwave radiation is not uncommon. In the analysis that follows (A_{pan}/A_{rc}) = 1.15 is assumed throughout but when a measured value for (A_{pan}/A_{rc}) is available, this should be used in equation (14) instead.

The crop water estimation framework established in FAO-56 (in particular, the tables of crop coefficients) are assumed to apply best when the wind speed is 2 m s^{-1}. It is therefore reasonable to adopt u_2 = 2 m s^{-1} as the default value of wind speed in equation (14). In addition and as previously mentioned, Shuttleworth & Wallace (2009) recommend using a preferred temperature of 20°C when calculating the unstressed value of surface resistance for crops from the crop coefficient values tabulated in FAO-56. In the absence of any better alternative value, T_2 = 20°C is therefore recommended for use as the default value for temperature in equation (14).

An analysis was made to investigate the effect of having ancillary weather data available with which to improve the estimate of K_p that would otherwise have to be calculated by substituting the default wind speed (2 m s^{-1}) when calculating the aerodynamic resistances and the default temperature (20°C) when calculating the value of Δ in equation (14). One thousand randomly sampled values of temperature were uniformly selected over the range 0 to 40°C together with randomly sampled wind speed uniformly over the range 0 to 7 m s^{-1} and randomly sampled values of (A_{pan}/A_{rc}) uniformly selected over the range 1.1 to 1.2. For each of these combinations of randomly selected variables, the "true" value of K_p was then calculated from equation (14) using the randomly selected values with atmospheric pressure set to 100 kPa (pressure is required for the calculation of γ). A comparison was then made between these true values of K_p and the value of K_p calculated when either temperature, or wind speed, or both, were not measured, and either default or estimated values had to be assumed. Figure 8 shows a comparison between the true value of K_p and that calculated with default or measured variables.

Table 2 gives the root mean squared error (RMSE) of the values of K_p made with default or estimated values of wind speed and temperature relative to the true value of K_p. Focusing first on the bold-font values in Table 2, when both temperature and wind speed are measured but the fixed value (A_{pan}/A_{rc}) = 1.15 is used in equation (14), the RMSE is around 0.01 in both humid and arid conditions. However, the RSME increases to around 0.15 in humid conditions and 0.12 in arid conditions when both variables are unmeasured and default values are used. By itself the

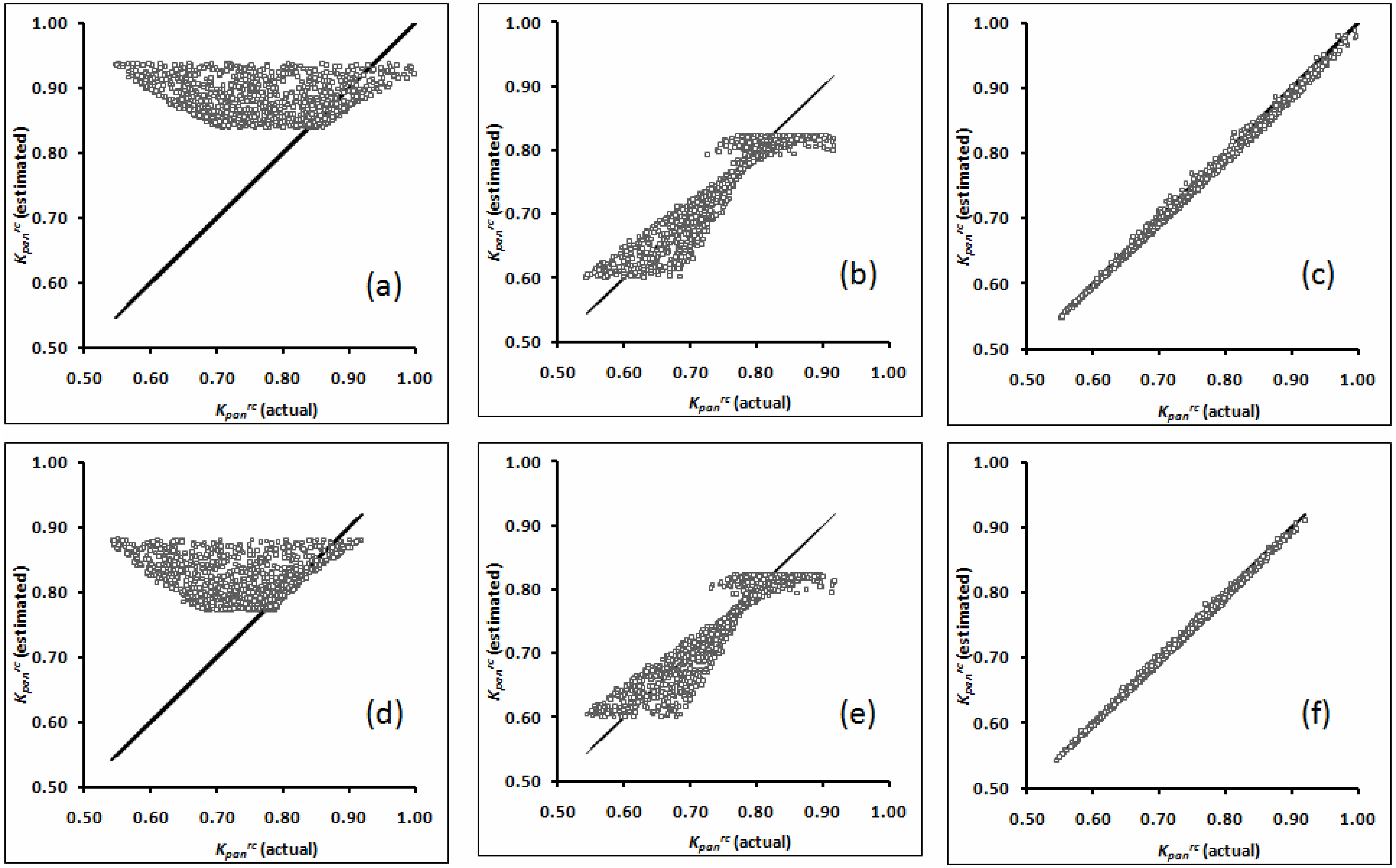


Fig. 8 Comparison between the value K_p calculated from equation (14) for randomly selected but assumed accurately measured values of (A_{pan}/A_{rc}), wind speed, and temperature (see text for selection ranges) on the *X* axis, compared with the value calculated from equation (14) with (A_{pan}/A_{rc}) set to 1.15 and, in the case of (a) and (d), the correct measured temperature with wind speed assumed unmeasured and set to 2 m s^{-1}; in the case of (b) and (e), the correct, measured wind speed but temperature assumed unmeasured and set to 20°C; and in the case of (c) and (f), both temperature and wind speed correctly measured. The values shown in (a), (b) and (c) are calculated in humid conditions, and in (d), (e) and (f) in arid conditions.

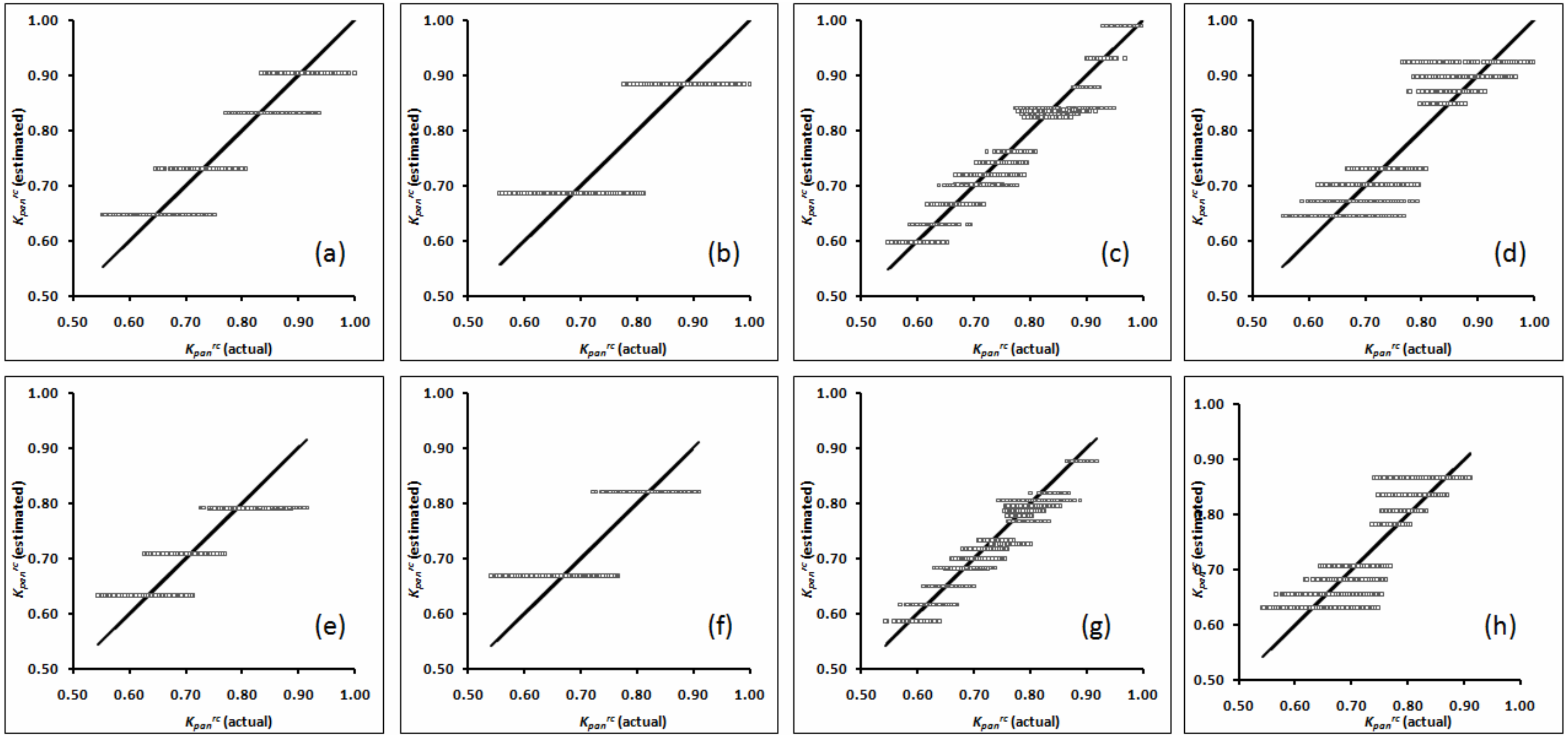


Fig. 9 The value K_p calculated from equation (14) for randomly selected but assumed accurately measured values of (A_{pan}/A_{rc}), wind speed, and temperature compared with the value calculated from equation (14) with (A_{pan}/A_{rc}) set to 1.15 and, in the case of (a) and (e), the (unmeasured) wind speed estimated to within 2 m s^{-1} with the unmeasured temperature set to 20°C; in the case of (b) and (f), the unmeasured wind speed estimated to within 4 m s^{-1} and unmeasured temperature set to 20°C; in the case of (c) and (g), the unmeasured wind speed estimated to within 2 m s^{-1} and unmeasured temperature estimated to within 20°C; and in the case of (d) and (h), the unmeasured wind speed estimated to within 4 m s^{-1} and unmeasured temperature estimated to within 20°C. The values shown in (a), (b), (c) and (d) are calculated in humid conditions, and in (e), (f), (g) and (h) in arid conditions.

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Table 2 Root mean square error (RMSE) relative to the "true" value when K_p is calculated from equation (14) with the values of temperature and wind speed defined in different ways, i.e., fixed at 20°C and 2 s m^{-1} (because no information is available); when available as measured values; or when temperature is estimated to the nearest 10 or 20°C and/or wind speed is estimated to the nearest 2 or 4 m s^{-1}.

	T measured	*T* fixed at 20°C	*T* estimated to 5°C	*T* estimated to 10°C
Humid conditions				
u measured	**0.01**	**0.03**	0.01	0.01
u fixed at 2 m s^{-1}	**0.15**	**0.15**	0.16	0.16
u estimated to 2 m s^{-1}	0.03	0.04	0.03	0.03
u estimated to 4 m s^{-1}	0.05	0.06	0.05	0.05
Arid conditions				
u measured	**0.01**	**0.03**	0.01	0.01
u fixed at 2 m s^{-1}	**0.12**	**0.12**	0.13	0.13
u estimated to 2 m s^{-1}	0.03	0.04	0.03	0.03
u estimated to 4 m s^{-1}	0.04	0.05	0.04	0.04

availability of a temperature measurement gives no worthwhile reduction in the RSME in this study, but if a wind speed measurement is available there is a substantial reduction to an RSME of about 0.03 regardless of whether temperature is measured.

The remaining values of RSME given in Table 2 correspond to cases when K_p is calculated using approximate estimates of temperature and wind speed rather than measured values. In both humid and arid conditions, the two right-hand side columns are when temperature is assumed to be estimated to an accuracy of 5°C and 10°C, respectively. (For example, if the randomly selected temperature falls in the range 5–10°C, the value 7.5°C was used when the calculation is to an accuracy of 5°C, and if the randomly selected temperature is in the range 20–30°C, the value 25°C was used when the calculation was to an accuracy of 10°C.) In the lower two rows, wind speed is assumed to be estimated to an accuracy of 2 s m^{-1} and 4 s m^{-1}, respectively. Figure 9 shows comparisons between the true value of K_p and the value calculated using values of wind speed and temperature estimated with a specified accuracy corresponding to example elements of Table 2. Together Fig. 9 and Table 2 demonstrate that estimating temperature when measurements are not available has little value when specifying K_p, but that even coarse estimates of wind speed (made to an accuracy of just 4 m s^{-1}) have some value and reduce the RMSE from 0.15 to 0.06 in humid conditions, and from 0.12 to 0.05 in arid conditions. Obviously estimates of wind speed with greater accuracy have greater benefit in reducing RSME.

Examples from Australian pan data The analysis given in the last section implicitly assumes (a) that the value of climatological resistance can be correctly assigned by substituting $\alpha = 1.26$ or $\alpha = 1.74$ into equation (6) in humid of arid conditions, respectively; and (b) that the form for pan aerodynamic resistance given by Rotstayn *et al*. (2006) with $C_{pan} = 224$ used in equation (12) is universally applicable (despite the site-to-site variability apparent in Fig. 2). Monthly data from two of the pan sites in Australia used in the Roderick *et al*. (2007) analysis were selected to investigate the limitations that may result from these two assumptions. The two selected sites were Australian Bureau of Meteorology pan sites at Cairns airport (Lat. –16.8736; Long. 145.7458; Alt. 3 m) and Alice Springs airport (Lat. –23.7951; Long. 133.8890; Alt. 546 m). The meteorological and pan data (when available) were provided as monthly average values. The 84-month period between January 1997 and December 2003 was selected, this being a period over which data were available for both sites for a reasonable proportion of the time.

At these sites, average temperature, wind speed, dew point temperature, pressure, and incoming solar radiation were measured, these variables being sufficient to allow calculation of reference crop evaporation using standard equations; see, for example, Shuttleworth (1993). Mean cloud cover was estimated by comparing the measured monthly-average incoming solar radiation

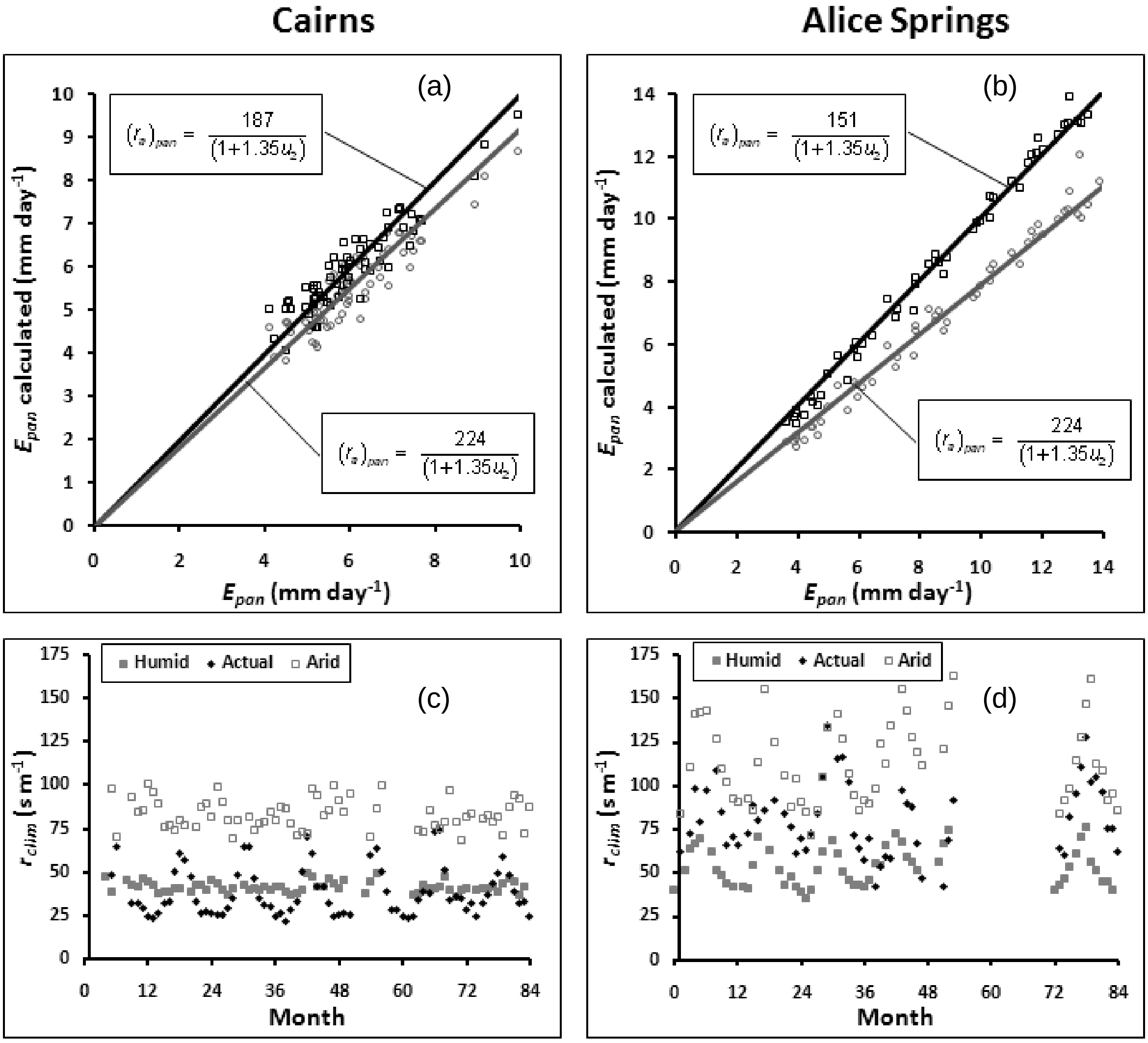

Fig. 10 (a) and (b), respectively, show comparisons over the same time period between measured monthly average pan evaporation at the Cairns and Alice Springs pan sites and values calculated from the Penman equation using meteorological data at these sites. In (a) and (b), the grey coloured symbols and fitted line relate to pan evaporation calculated with the Penpan equation using the average value of C_{pan} = 224 reported for all Australian sites by Roderick *et al*. (2007). The black symbols and lines are values calculated with optimized site-specific values of C_{pan} = 187 for the Cairns site and C_{pan} = 151 for the Alice Springs site. (c) and (d), respectively, show the values of actual monthly average climatological resistance at the Cairns and Alice Springs pan sites (when sufficient data are available) between January 1997 and December 2003 compared with values in humid and arid conditions calculated from equation (6) with α = 1.26 and α = 1.74, respectively.

with the calculated monthly-average solar radiation incident at the top of the atmosphere assuming 25% of solar radiation is absorbed in clear sky conditions. From this estimate of cloud cover, net longwave radiation and hence net radiation were then calculated. Monthly average estimates of pan evaporation rates were also made at each site from these data using the Penpan equation and compared with the measured rates. The results shown in Fig. 10(a) and (b) showed that there were significant, systematic differences between the estimated and measured pan evaporation rates when the all-pan average value of C_{pan} = 224 was used at these two sites, but that this discrepancy was removed when the values of C_{pan} were separately optimized to the values C_{pan} = 187 for the Cairns site and C_{pan} = 151 for the Alice Springs site.

A monthly average diagnosis of atmospheric humidity was also made by calculating the actual value of climatological resistance calculated at each site from equation (5) and comparing this with the value calculated from equation (6) with $\alpha = 1.26$ and $\alpha = 1.74$. The results shown in Fig. 10(c) and (d) suggest that the (coastal) Cairns site is clearly humid, indicating use of $\alpha = 1.26$ when calculating r_{clim} in equation (14) at this site, while the (inland) Alice Springs site is significantly more arid, suggesting that assuming $\alpha = 1.74$ is more appropriate when calculating r_{clim} in equation (14) at this site.

Figure 11 compares the monthly average reference crop evaporation calculated from measured weather variables compared with the values estimated from measured pan evaporation with K_p calculated from equation (14) in different ways. In all cases (A_{pan}/A_{rc}) is set to 1.15. Figure 11(a), (b) and (c) are for the Cairns pan site and calculated with r_{clim} calculated $\alpha = 1.26$, while Fig. 11(d), (e), and (f) are for the Alice Springs site with r_{clim} calculated $\alpha = 1.74$. In Fig.11(a) and (d) K_p is calculated using the default values $u_2 = 2$ m s^{-1} and $T_2 = 20$°C and assuming the all pan average value of $C_{pan} = 224$. In Fig. 11(b) and (e) the same default values of u_2 and T_2 are used but C_{pan} is set to the optimized site-specific values (i.e. 187 for Cairns and 151 for the Alice Springs). In Fig. 11(c) and (f), K_p is calculated as for (b) and (e) but the measured value of u_2 is used rather than a fixed value of 2 m s^{-1}.

On the basis of Fig. 11, it is clear that knowledge of the site specific value of C_{pan} is important if the formal definition of K_{pan} is to be used to improve estimates of reference crop evaporation

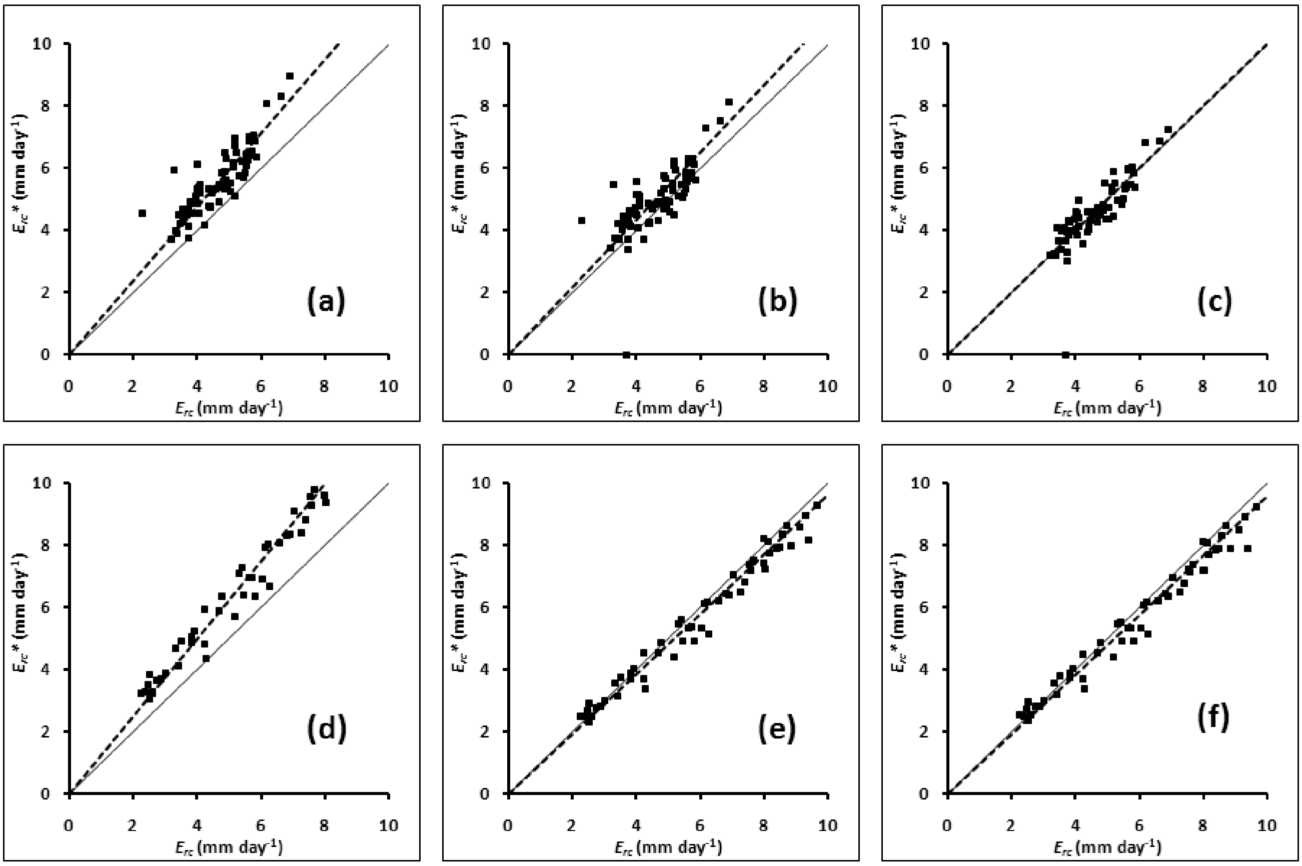

Fig. 11 Comparison between monthly average reference crop evaporation calculated from measured weather variables using the equation recommended by FAO-56 compared with the values estimated from measured pan evaporation with K_p calculated from equation (14). (a), (b) and (c) are for the Cairns pan site and calculated with r_{clim} calculated from equation (6) with $\alpha = 1.26$, while (d), (e), and (f) are for the Alice Springs site with r_{clim} calculated from equation (6) with $\alpha = 1.74$. In all cases (A_{pan}/A_{rc}) is set to 0.15. In (a) and (d) K_p is calculated using the default values $u_2 = 2$ m s^{-1} and $T_2 = 20$°C and assuming $C_{pan} = 224$, while in (b) and (e) the same default values of u_2 and T_2 are used but C_{pan} is set to optimized site specific values (i.e. 187 for Cairns and 151 for the Alice Springs). In (c) and (f), K_p is calculated as for (b) and (e), but the measured value of u_2 is used rather than 2 m s^{-1}.

derived from pan evaporation rate. Most of the improvement in the relationship between Fig. 11(a) and (c) and between Fig. 11(d) and (f) is associated with the better definition of the value of C_{pan}. There is some evidence of an improvement between Fig. 11(b) and (c) associated with the use of the measured value of wind speed rather than assuming u_2 = 2 m s^{-1} but the clarity with which this improvement is demonstrated in this analysis is heavily compromised by the fact that monthly average values of weather variables are used. The results would likely be more obvious were daily data to be used. The fact that monthly average data are used is also the reason why there is even less evidence of an improvement between Fig. 11(e) and (f) because, in practice, the monthly (as opposed to daily) average wind speed is often close to 2 m s^{-1} at this inland site.

4 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This paper makes a critical reappraisal of currently recommended methods for estimating the water requirements of irrigated crops in light of present-day knowledge of the evaporation process for vegetation covered surfaces and evaporation pans.

The review of recent literature relating to estimating the water requirements of irrigated crops reveals that there is now no longer a need to resort to use of the two-step estimation procedure currently recommended by FAO. The alternative, the Matt-Shuttleworth approach which involves use of the more theoretically rigorous Penman-Monteith equation for *all* crops, is preferable because:

(a) it is consistent with present day understanding of the physical and physiological controls of the evaporation processes (which the FAO two step approach is not);
(b) readily available methods for applying the M-S approach using standard 2-m climate station data are available;
(c) a simple methodology for converting values of crop coefficients to the required values surface resistance has been defined (based on crop height and assuming T^{pref} = 20°C);
(d) use of the values of surface resistance so determined in the M-S approach will yield estimates of evaporation which are at least as good as those given by using the FAO-56 approach but which have improved representation of the effect of atmospheric aridity and of within season variability in weather variables;
(e) future understanding of crop responses to weather, crop development, leaf area, and soil conditions will be aided by the adoption of a more realistic representation of plant control in the form of surface resistance; and
(f) use of a surface resistance to represent crop behaviour will facilitate future improvements in the calculation of the water requirements of crops with partial ground cover via use of two-source resistance (soil and crop) based models (e.g. Shuttleworth & Wallace, 1985).

The results of the investigation into the potential benefits of applying the recently developed Penpan equation and the associated formal definition of the pan factor, equation (14), are less definitive. The theoretical analysis given clearly shows that the ratio of the available energy for a reference crop to that for a pan has little influence on pan factor and that assuming (A_{pan}/A_{rc}) = 1.15 is usually a reasonable assumption giving accuracy within a few percent. The analysis also suggests temperature has limited influence except at very low and very high wind speeds, but that some knowledge, even approximate knowledge, of wind speed is very important when estimating the pan factor. This theoretical analysis, however, assumes the universal applicability of the form for pan aerodynamic resistance given by Rotstayn *et al*. (2006) with C_{pan} = 224 used in equation (12), and also that the value of climatological resistance can be correctly assigned by substituting α = 1.26 or α = 1.74 into equation (6) in humid or arid conditions, respectively. Arguably the second assumption has less impact on accuracy than the former because the atmospheric aridity of pan sites is often fairly well known. But it is clear from Fig. 11 that use of a site-specific value of C_{pan} at a particular pan site is critical if applying the Penpan equation is to have practical benefit in improving estimates of reference crop evaporation. It is also clear that were a calibration of C_{pan} at a specific pan site to be made (perhaps by temporarily deploying the sensors needed to gather the weather data required by the Penpan equation), then the subsequently sustained collection of wind speed measurement would by itself greatly improve the accuracy of pan based estimates of reference crop evaporation at the site.

On the basis of the results of this study, the following two main recommendations are made:

(a) A transition towards making estimates of crop water requirements in irrigation practice based on the one-step Matt-Shuttleworth approach rather than the currently recommended FAO-56 approach should be initiated, beginning with the translation of existing tabulated values of crop coefficients into equivalent values of surface resistance for all crops.

(b) Pan-based estimates of reference crop evaporation rate should be made with recognition of the now-available theoretical formula for pan coefficient, i.e. equation (14) (with appropriate acknowledgement of the likelihood that C_{pan} may be pan specific), and preferably using nearby measurements of wind speed and temperature if available, or estimates of their values otherwise.

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APPENDIX

Using 2-m weather variables in the P-M equation for all crops

Shuttleworth (2006) defined how 2-m climate data can be used to calculate evaporation from any crop using the P-M equation by assuming a hypothetical common "blending height" at 50 m at which the P-M equation is applied. To apply this equation, it is necessary to calculate the aerodynamic resistance between 50 m and the crop of interest from the wind speed measured at 2 m, and also the value of the vapour pressure deficit (VPD) at 50 m from the VPD measured at 2 m. The assumptions Shuttleworth (2006) uses are that:

(1) there is no "flux divergence" between 2 m and 50 m, i.e. the fluxes of momentum, water vapour, sensible heat, and net radiation are the same at the two levels;
(2) the wind speed profile above the 2-m measurement location is adequately described by the logarithmic profile applicable in neutral atmospheric conditions; and
(3) the aerodynamic resistance for *all* crops is adequately described by equation (3) assuming $z_0 = 0.123h_c$ and $d = 0.67h_c$, where h_c is the height of the crop.

Details of how these assumptions are used are given in Shuttleworth (2006) to which the reader is referred. In outline, assumptions (1) and (2) are first used to calculate the wind speed at 50 m. The aerodynamic resistance to 50 m for the crop then follows immediately from assumption (3) and is given in the form $(r_a)_c = R_c^{50}/u_2$, where:

$$R_c^{50} = \frac{1}{(0.41)^2} \ln\left[\frac{(50 - 0.67h_c)}{(0.123h_c}\right] \ln\left[\frac{(50 - 0.67h_c)}{(0.0123h_c}\right] \frac{\ln\left[\frac{(2 - 0.08)}{0.0148}\right]}{\ln\left[\frac{(50 - 0.08)}{0.0148}\right]} \quad \text{(A1)}$$

The P-M equation is then applied to the reference crop surface at two levels (2 m and 50 m) assuming the same value (70 s m^{-1}) for surface resistance, and with the appropriate aerodynamic resistances for a 2-m reference level ($208/u_2$) and 50-m reference level ($302/u_2$), the value 302 being that given by equation (A1) with $h_c = 0.12$ m. Assumption (1) implies that the calculated evaporation flux given by these two applications of the P-M equation must be equal and also that the available energy at the two levels is the same. By equating these two P-M calculations of fluxes, the ratio of the VPD at 50 m to that at 2 m, (D_{50}/D_2), can be calculated from:

$$\frac{D_{50}}{D_2} = \left(\frac{(\Delta + \gamma)302 + 70\gamma u_2}{(\Delta + \gamma)208 + 70\gamma u_2}\right) + \frac{1}{r_{\mathrm{clim}}}\left[\left(\frac{(\Delta + \gamma)302 + 70\gamma u_2}{(\Delta + \gamma)208 + 70\gamma u_2}\right)\left(\frac{208}{u_2}\right) - \frac{302}{u_2}\right] \quad \text{(A2)}$$

Deriving values of surface resistance from crop factors

The origin of the crop factors given by FAO-56 and the experimental conditions where these were derived are not specified, although the crop factor values are said to be appropriate for wind speeds of 2 m s^{-1}. Shuttleworth (2006) derived a conversion method from crop factor to surface resistance which exploits the fact that the original FAO-24 recommendations of Doorenbos & Pruitt (1977) are said to be a primary source of the values of crop factors given in FAO-56 (Allen *et al.*, 1998), and in Doorenbos & Pruitt (1977) these FAO crop factors were considered applicable to a range of estimates of potential evapotranspiration based on different estimation formulae, including the Priestley-Taylor equation applied in humid conditions.

There is an important parallel between FAO's recommended procedure for estimating crop evapotranspiration and complementary modelling studies carried out independently by the meteorological community interested in understanding the coupling between surface exchanges and the overlying atmospheric boundary layer. As discussed in detail by Shuttleworth (2006), there is a range of preferred weather conditions in which the reference crop evapotranspiration rate calculated by the FAO-56 equation and the equivalent rate calculated by the Priestley-Taylor equation are approximately equal. Shuttleworth argues that it is within this range of conditions that the concept of potential rates is most likely to have validity and that the values of crop factors given by FAO-56 (1998) (hereafter called K_c^{FAO}) are most likely acceptable for use for estimating reference crop evapotranspiration. The particular conditions when the FAO-56 reference crop and Priestley-Taylor equations are equal and when K_c^{FAO} likely applicable are, therefore, those described as "humid atmospheric conditions" above, i.e. when the climatological resistance is that given by equation (6) with $\alpha = 1.26$.

Thus, in the absence of information on the climate conditions during the calibration of K_c^{FAO}, it is necessary to assume that the values given are optimum when used in humid conditions. However, because FAO-56 states that the wind speed for which K_c^{FAO} values apply is 2 m s^{-1}, this wind speed can be substituted into equation (6) to give an estimate of $(r_{\text{clim}})^{pref}$ that then depends solely on T^{pref}, the "preferred" temperature considered typical of the period when the value of K_c^{FAO} was calibrated, thus:

$$(r_{\text{clim}})^{pref} = 104\left(1.26\frac{\Delta^{pref} + 1.67\gamma}{\Delta^{pref} + \gamma} - 1\right) \tag{A3}$$

where Δ^{pref} is the value of Δ calculated at the temperature T^{pref}. At this preferred temperature, Shuttleworth (2006) showed that the value of the surface resistance for a well watered crop equivalent to the FAO crop coefficient, $(r_s)_c$, can be calculated from:

$$(r_s)_c = \frac{r_s^1}{K_c^{FAO}} - r_s^2 \tag{A4}$$

where:

$$r_s^1 = \left(\frac{\dfrac{R_c^{50}}{u_2} + \left(\dfrac{D_{50}}{D_2}\right)^{pref}(r_{\text{clim}})^{pref}}{\dfrac{302}{u_2} + \left(\dfrac{D_{50}}{D_2}\right)^{pref}(r_{\text{clim}})^{pref}}\right)\left(\frac{(\Delta^{pref} + \gamma)\dfrac{302}{u_2} + 70\gamma}{\gamma}\right) \tag{A5}$$

$$r_s^2 = \frac{(\Delta^{pref} + \gamma)}{\gamma}\frac{R_c^{50}}{u_2} \tag{A6}$$

with $(D_{50}/D_2)^{pref}$ given by equation (A2) when $\Delta = \Delta^{pref}$ and u_2 = 2 m s^{-1}. The values of r_s^1 and r_s^2 are solely functions of the crop height and the temperature (known or assumed) at which the FAO crop factor was calibrated. Shuttleworth & Wallace (2009) show that for several important irrigated crops there is limited sensitivity to the assumed value of T^{pref} and they recommend that, in the absence of better information, T^{pref} = 20°C is used in equations (A4), (A5) and (A6).