Hydrol. Earth Syst. Sci., 19, 583–599, 2015
www.hydrol-earth-syst-sci.net/19/583/2015/
doi:10.5194/hess-19-583-2015

Hydrology and
Earth System
Sciences
Open Access

Divergence of actual and reference evapotranspiration observations for irrigated sugarcane with windy tropical conditions

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Received: 9 May 2014 – Published in Hydrol. Earth Syst. Sci. Discuss.: 17 June 2014
Revised: 21 November 2014 – Accepted: 25 November 2014 – Published: 29 January 2015

Abstract. Standardized reference evapotranspiration (ET) and ecosystem-specific vegetation coefficients are frequently used to estimate actual ET. However, equations for calculating reference ET have not been well validated in tropical environments. We measured ET ($\mathrm{ET_{EC}}$) using eddy covariance (EC) towers at two irrigated sugarcane fields on the leeward (dry) side of Maui, Hawaii, USA in contrasting climates. We calculated reference ET at the fields using the short ($\mathrm{ET_0}$) and tall ($\mathrm{ET_r}$) vegetation versions of the American Society for Civil Engineers (ASCE) equation. The ASCE equations were compared to the Priestley–Taylor ET ($\mathrm{ET_{PT}}$) and $\mathrm{ET_{EC}}$. Reference ET from the ASCE approaches exceeded $\mathrm{ET_{EC}}$ during the mid-period (when vegetation coefficients suggest ET_{EC} should exceed reference ET). At the windier tower site, cumulative $\mathrm{ET_r}$ exceeded $\mathrm{ET_{EC}}$ by 854 mm over the course of the mid-period (267 days). At the less windy site, mid-period $\mathrm{ET_r}$ still exceeded $\mathrm{ET_{EC}}$, but the difference was smaller (443 mm). At both sites, $\mathrm{ET_{PT}}$ approximated mid-period $\mathrm{ET_{EC}}$ more closely than the ASCE equations (($\mathrm{ET_{PT}}$-$\mathrm{ET_{EC}}$) < 170 mm). Analysis of applied water and precipitation, soil moisture, leaf stomatal resistance, and canopy cover suggest that the lower observed $\mathrm{ET_{EC}}$ was not the result of water stress or reduced vegetation cover. Use of a custom-calibrated bulk canopy resistance improved the reference ET estimate and reduced seasonal ET discrepancy relative to $\mathrm{ET_{PT}}$ and $\mathrm{ET_{EC}}$ in the less windy field and had mixed performance in the windier field. These divergences suggest that modifications to reference ET equations may be warranted in some tropical regions.

1 Introduction

Accurate estimates of evapotranspiration (ET) are needed for numerous purposes, including efficient irrigation scheduling (Davis and Dukes, 2010), parameterizing and running different classes of biogeochemical and hydrologic models (Fisher et al., 2005; Zhao et al., 2013), assessing changes in regional hydrology under different cultivation systems (Ferguson and Maxwell, 2011; Holwerda et al., 2013; Waterloo et al., 1999), and evaluating the impacts of agricultural production on regional and global climate (Kueppers et al., 2007; Lo and Famiglietti, 2013; Puma and Cook, 2010) and hydrology (Anderson et al., 2012; Vörösmarty et al., 1998). In irrigated agriculture, underestimation of required ET can lead to suboptimal yield due to water stress (Kang et al., 2002), whereas overestimation of ET can lead to excessive applied water, thus reducing water available for other uses or additional acreage (Perry, 2005), degrading water quality (Smith, 2000), and decreasing economic competitiveness (Hargreaves and Samani, 1984).

While accurate ET estimates are essential, ET can be challenging to measure. Numerous approaches have been developed to measure or estimate ET, including lysimeters (Meissner et al., 2010), micrometeorological methods (Anderson and Goulden, 2009; Baldocchi, 2003; Hemakumara et al., 2003), satellite remote sensing (Bastiaanssen et al., 2005; Tang et al., 2009), and water balance methods. While these approaches vary in their spatial/temporal scale and methodological assumptions and accuracy, most require significant

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observational costs, technical expertise, or have operational difficulties that are too high for most farmers.

Because of the difficulties in actual ET measurement, the vegetation coefficient/reference ET approach (Jensen, 1968) has gained widespread acceptance for estimating actual ET for varied applications (e.g., Arnold et al., 1998; Cristea et al., 2013). This approach involves calculating a reference ET for a standard land surface, usually grass or alfalfa, using meteorological data and relating the reference surface to the ecosystem/land cover of interest with empirical coefficient(s):

$$\mathrm{ET_A} = K_\mathrm{C} * \mathrm{ET_0}, \tag{1}$$

where $\mathrm{ET_A}$ is actual ET, $\mathrm{ET_0}$ is reference ET, and K_c is the coefficient for the specific land cover type. Two of the most commonly used standard methods include the Food and Agricultural Organization (FAO) approach presented in Irrigation and Drainage paper 56, hereafter referred to as FAO-56 (Allen et al., 1998), and the American Society of Civil Engineers approach, hereafter referred to as ASCE (Allen et al., 2005). Both approaches are based on the combination Penman–Monteith (PM) formula (Monteith, 1965) and account for ET from both solar irradiation and advectively driven ET due to wind and vapor pressure deficit (VPD). Both the FAO-56 and ASCE approaches assume standard measurement conditions and surface parameters (canopy height, surface resistance, albedo, etc.), thus allowing canopy and atmospheric resistance terms to be condensed into constants. Both methods also provide scaling procedures to account for variation in meteorological measurements as well as missing or erroneous data.

Validation work of standardized reference ET equations against large weighing lysimeters with reference surfaces has been done primarily in the western continental USA with low atmospheric humidity (Evett et al., 2000; Jensen et al., 1990). Internationally, most other reference ET validation has been done in Mediterranean climates with similar low humidity (Lecina et al., 2003; Ventura et al., 1999). Relatively little evaluation of these equations has been done in areas with higher relative humidity, presumably because of the perceived lack of use for reference ET equations in these areas. However, reference ET equations are used in more humid regions for applications such as watershed modeling (Rao et al., 2011), forecasting water demand (Tian and Martinez, 2012), and determining irrigation needs (Suleiman and Hoogenboom, 2007). As such, it is necessary to test these reference ET equations in regions with high relative humidity to ensure accurate ET parameterization.

One major tropical and subtropical crop that has generally high ET is sugarcane. Sugarcane is a good crop to test reference ET parameterizations because of its longer full-canopy period, when actual crop ET should be at its maximum relative to reference ET equations, and its high crop coefficient (K_c) that generally exceeds 1. Previous research in irrigated sugarcane has found full-canopy ET rates that equal or exceed evaporation rates from open-water pans (Campbell et al., 1960; Thompson and Boyce, 1967). Since the development and implementation of reference ET equations, researchers have generally found irrigated sugarcane to have a K_c greater than 1 in Australia and Swaziland (Inman-Bamber and McGlinchey, 2003), Brazil (Da Silva et al., 2012), and Texas (Salinas and Namken, 1977). However, all of these studies found variable and differing K_c values, with Inman-Bamber and McGlinchey noting a correspondence between meteorological events and outlying daily K_c values. Sugarcane's high water use, the potential for expanded irrigation to reduce yield deficits and increase production in tropical regions (Inman-Bamber et al., 1999), and the potential for sugarcane irrigation to stress water resources during dry periods in tropical areas (Ramjeawon, 1994) make it a good case study for evaluating reference ET equations in tropical regions.

To evaluate the performance of standardized reference ET equations, we established two eddy covariance (EC) towers over irrigated sugarcane fields in Hawaii, USA to measure ET ($\mathrm{ET_{EC}}$). We calculated reference ET using the ASCE approach for short ($\mathrm{ET_0}$) and tall ($\mathrm{ET_r}$) reference vegetation. The FAO-56 $\mathrm{ET_0}$ was not used as it is identical to ASCE $\mathrm{ET_0}$ for calculations on a daily time step (Irmak et al., 2006; Suleiman and Hoogenboom, 2009). We also compared $\mathrm{ET_{EC}}$ to the Priestley–Taylor (PT) ET equation ($\mathrm{ET_{PT}}$). Our objectives were to (1) determine if standardized reference ET equations adequately parameterized actual ET across differing microclimates, (2) determine the meteorological conditions that contribute to discrepancies in the standardized equations, and (3) examine corrections to improve estimates of reference ET under relatively more humid conditions.

2 Methods

2.1 Study region

We evaluated reference ET approaches in two sugarcane (*Saccharum officinarum* L.) fields with identical cultivars (Heinz et al., 1981) at a commercial farm on Maui, Hawaii (Fig. 1 and Table 1). Climatic conditions vary across the farm, with changes in precipitation, wind, solar irradiation, and air temperature due to orographic effects. Normal annual precipitation ranges from 275 to 1275 $\mathrm{mm\,year^{-1}}$ from the leeward (south) side to the windward (northeast) side of the plantation (Giambelluca et al., 2013). Elevations on the plantation range from near sea level to ~ 340 m. The western side of the plantation is generally windier (Table 1). Drip irrigation is used to maximize limited surface and ground water resources (Moore and Fitschen, 1990). Drip tape spacing is 2.70 m with sugarcane rows planted 45 cm away from the tape on both sides; the tape irrigates at $1.58\,\mathrm{L^{-1}\,h^{-1}\,m^{-1}}$ and is regulated to 83 kPa of pressure at the head of the row. Irrigation amounts were recorded by the farm; rainfall was

Table 1. Eddy covariance field site information.

Micrometeorological site information		
Field	Lee	Windy
Latitude (°N)	20.784664	20.824633
Longitude (°W)	156.403869	156.491278
Elevation (m)	203	44
Date field planted	28 March 2011	11 May 2011
Date tower established	21 July 2011	23 July 2011
Begin of mid-period (cover > 80 %)	3 November 2011	5 December 2011
End of analysis	26 July 2012	27 August 2012
Natural Resource Conservation Service (NRCS) soil series	Waiakoa very stony, silty clay loam	Pulehu cobbly silt loam
Bulk density*	1.22	1.35
Porosity (%)	54	49
Soil texture classification**	Clay	Sandy clay loam
Soil texture – sand (%)	31	51
Soil texture – silt (%)	15	16
Soil texture – clay (%)	54	33
Soil volumetric water content (VWC) at saturation (mm/40 cm depth)	216	196
Soil water storage (water content at 30 % VWC-wilting point) (mm)	60	72
Wilting point (% VWC)	15	12
Matric potential at 30 % VWC (MPa)	NA***	−0.01
Matric potential at 24 % VWC (MPa)	NA	−0.033
Field size (ha)	99.1	62.6
Field length (m) (predominant wind)	> 500	415
Field length (m) (shortest direction)	220	150
Mean meteorological observations (1 August 2011–31 July 2012)		
Mean daily air temperature (°C)	22.3	23.4
Mean minimum daily air temperature (°C)	17.8	20.4
Mean maximum daily air temperature (°C)	27.3	26.9
Mean daily wind speed ($\mathrm{m\,s^{-1}}$)	2.0	4.6
Mean daily net radiation ($\mathrm{MJ\,m^{-2}\,day^{-1}}$)	10.7	11.3
Mean daily relative humidity (%)	65	62

* All reported soil properties averaged/summed over the first 40 cm of soil depth. ** Soil texture was determined in the lab using the hydrometer method. ** Matric potential not available for Lee because of extreme logistical difficulty in obtaining intact Tempe cell samples at depth for determination of water retention characteristics.

recorded at nearby weather stations (Supplement S1). As is typical for Hawaii (Heinz and Osgood, 2009), sugarcane is grown on a 24-month rotation with planting and harvesting throughout most of the year. Peak ET, as determined by the length of the mid-season period, lasts significantly longer (330 days) than for sugarcane in other regions (190–220 days) (Doorenbos and Pruitt, 1977; Inman-Bamber and McGlinchey, 2003).

2.2 EC measurements and data analysis

We installed two micrometeorological towers in contrasting micro-climates (Fig. 1 and Table 1). These towers are at the "Windy" site (lower elevation, higher wind velocity, more constant wind direction, and sandy clay loam soil) and the "Lee" site (higher elevation, lower wind velocity, and clay soil). Field fetch in the prevailing wind directions was over 200 m for both towers. The slope in both fields, as determined using the 1/3 arcsec (∼ 10 m) digital elevation model from the US Geological Survey's National Elevation Dataset (http://ned.usgs.gov/index.html), is less than 3 %. Beyond the edge of each field, Windy was surrounded by sugarcane fields on all sides for over 1500 m; Lee was bordered by non-irrigated rangeland in the non-prevailing wind directions (east and south) and contiguous sugarcane fields to the north and east.

Tower instrumentation included an integrated EC system (EC150 – Campbell Scientific, Logan, Utah, USA[1]) with an open-path infrared gas analyzer, aspirated temperature probe,

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[1] Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information

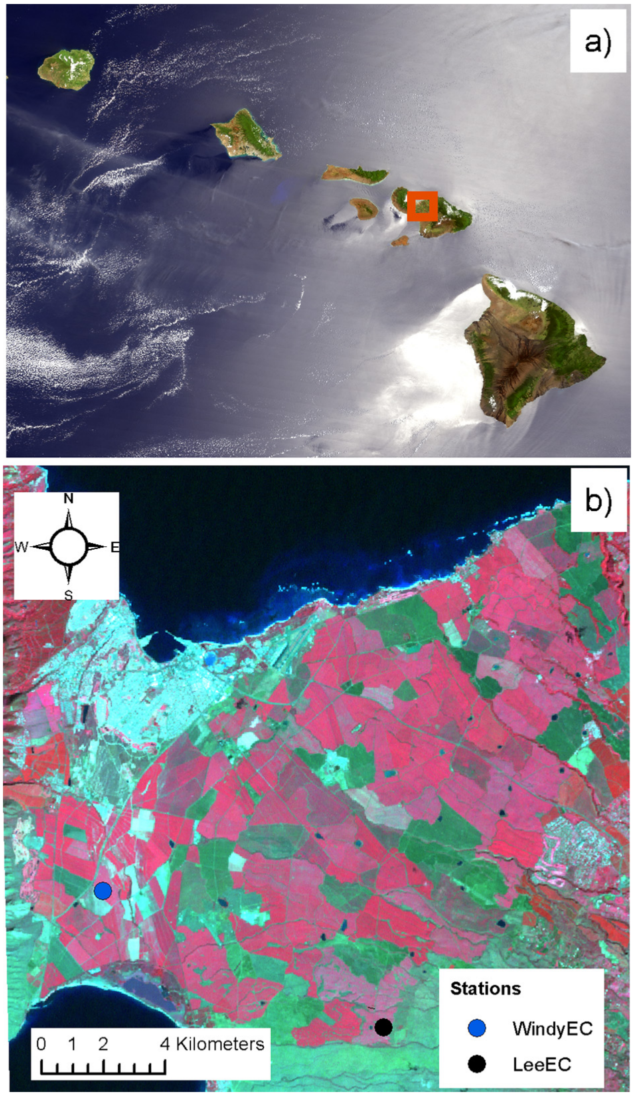

Figure 1. (a) True color image of the main Hawaiian islands from the moderate resolution imaging spectroradiometer (250 m resolution – image date: 27 May 2003). Study region is outlined in red box. **(b)** The study region on central Maui showing the location of the eddy covariance towers (Windy and Lee) used in this study. Image is false color Landsat 7 (30 m resolution – image date: 5 February 2000).

attached 3-D sonic anemometer head (CSAT3A – Campbell Scientific), and enhanced barometer (PTB110 – Vaisala, Vantaa, Finland). Relative humidity and air temperature were measured by a combined temperature and relative humidity probe (HMP45C – Vaisala). Net radiation was measured with a single component net radiometer (NR-Lite2 – Kipp and Zonen, Delft, Netherlands). We corrected the single component net radiometer for the effect of wind following Cobos and Baker (2003). Ground heat flux was measured as the average of four self-calibrating heat flux plates (HFP01SC – Hukseflux, Delft, Netherlands). The plates were installed at 5 cm depth at four lateral locations perpendicular to the irrigation drip line (Sect. 2.1): 0 cm (drip line), 45 cm (sugarcane row), 75 cm, and 135 cm (mid-point between drip lines). All instruments were factory calibrated to ISO 9001:2008 standards prior to deployment; data were recorded and processed on solid-state data loggers (CR3000, Campbell Scientific).

Two water content reflectometry probes (CS616 – Campbell Scientific) were installed at 20 cm depth at two locations perpendicular to the drip line (45 and 135 cm) to measure soil volumetric water content (VWC). These locations were chosen to correspond with the sugarcane row (center of root zone) and halfway between sugarcane rows. VWC was measured to independently assess potential water stress in both fields. VWC was calculated using a quadratic equation with empirically determined coefficients specific to each field following the manufacturer's recommendation. Soil water retention and permanent wilting point were also determined for Windy but, due to rockiness at the Lee site, could not be determined for Lee because of the logistical difficulty and equipment risk in obtaining intact Tempe cell samples below the surface. More technical details on soil calibrations are provided in Supplement S1.

The EC150 system measured CO_2, H_2O, wind velocity, and sonic temperature at 10 Hz. Other variables were averaged to 30 min fluxes. We processed raw covariances on the data logger and post-processed high-frequency time series data with commercial software (Eddy Pro Advanced V 3.0 and 4.0 – LI-COR, Lincoln, Nebraska USA). Data logger flux calculations were downloaded daily via a cellular modem. High-frequency (10 Hz) data and half-hourly fluxes were transferred monthly via a data card. Raw time series data were checked following the tests of Vickers and Mahrt (1997). Sonic anemometer tilt was corrected using double rotation (Kaimal and Finnigan, 1994); lags between the infrared gas analyzer and sonic anemometer were determined using maximum covariance. We corrected for density fluctuations (Webb et al., 1980), low pass filtering (Moncrieff et al., 1997), and high pass filtering (Moncrieff et al., 2004). Flux footprint lengths were calculated following Kljun et al. (2004), and quality flags were assigned following the CarboEurope standard (Mauder and Foken, 2011). We independently calculated stability (Obukhov, 1971). After installation, tower heights were periodically adjusted to keep meteorological instrumentation ~ 3.0–3.3 m above the zero-plane displacement height, which was assumed to be 67 % of canopy height (Arya, 2001). Canopy height was measured biweekly, concurrent with the vegetation cover observations (Sect. 2.4). Additional detailed EC cross-validation activities are described in Supplement S1.

Half-hourly fluxes with instrumentation errors flagged by the EC150 system, rainfall, or lack of turbulence (friction velocity $< 0.1\,\mathrm{m\,s^{-1}}$) were excluded. Excluded fluxes were gap-filled as a function of fluxes mea-

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sured from similar meteorological periods using the Max Planck Institute tool (http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/index.php) (Reichstein et al., 2005). Gap-filled fluxes were used to calculate daily and cumulative fluxes but were excluded from half-hourly analyses. We corrected fluxes for energy budget closure by regressing daily EC-observed available energy against measured available energy (net radiation minus ground heat flux) and forcing the regression through the origin, preserving the daily mean Bowen ratio and adjusting each day's ET by the regression slope for the entire study period (Anderson and Wang, 2014; Leuning et al., 2012).

2.3 Reference ET equations, corrections, and evaluation of controls

At each tower, daily and hourly reference ET was calculated using the ASCE short (ET_0) and tall (ET_r) reference equations, where short and tall refer to parameterized surfaces similar to well-watered fescue grass (short) and alfalfa (tall), with differences in the equations due to assumed leaf area index (LAI) and bulk canopy resistance to ET:

$$\mathrm{ET}_\mathrm{sz} = \frac{0.408\Delta\left(R_\mathrm{n} - G\right) + \gamma \frac{C_\mathrm{n}}{T+273} u_2 \left(e_\mathrm{s} - e_\mathrm{a}\right)}{\Delta + \gamma\left(1 + C_\mathrm{d} u_2\right)}. \tag{2}$$

As shown in Eq. (2), ET_sz is the reference ET type (ET_r or ET_0 in mm day^{-1} or mm h^{-1} depending on time step); R_n and G are net radiation and ground heat flux (MJ m^{-2} day^{-1} or MJ m^{-2} h^{-1}), respectively; γ is the psychrometric constant (kPa °C^{-1}); T is mean daily or hourly air temperature (°C); u_2 is mean daily or hourly wind speed measured at or scaled to 2 m height; e_s and e_a are mean saturation and actual vapor pressure (kPa), respectively; and C_n and C_d are empirical numerator and denominator constants that change with the reference surface and time step (Table 1 in Allen et al., 2005). We scaled all meteorological variables from 3 m above the zero-plane displacement to 2 m, following the ASCE procedure for adjusting meteorological measurements at non-standard heights. Following ASCE, mean daily meteorological values were calculated as an average of daily minimum and maximum values as opposed to averaging all 24 h of measurements. Differences between these averaging approaches were small (mean T difference of 0.26 and 0.27 °C in Windy and Lee, respectively). Measured net radiation and ground heat fluxes were used for all calculations.

We also calculated another reference using the PT equation (Priestley and Taylor, 1972). PT was chosen as a comparison because of its different treatment of advection in comparison to the PM-type equations, its wide usage, and the relative simplicity of its meteorological inputs compared to PM. The PT equation is

$$\mathrm{ET}_\mathrm{PT} = \frac{\alpha}{\lambda} * \frac{\Delta\left(R_\mathrm{n} - G\right)}{\Delta + \gamma}. \tag{3}$$

ET_PT is the PT ET (mm day^{-1}); Δ, γ, R_n, and G are the same as in Eq. (2); λ is the latent heat of vaporization; and α is an empirical constant. We assumed that λ is 2.45 MJ mm^{-1}, which is the same as the ASCE/FAO-56 approach. We used an α of 1.26, which is widely, but not universally, representative of a well-watered surface across a variety of climates (e.g., Eichinger et al., 1996; McAneney and Itier, 1996).

To examine the discrepancies between the ASCE equations (ET_0 and ET_r), the PT equation (ET_PT), and measured ET_EC we inverted the PM equation to calculate bulk canopy resistance (r_c) from ET_EC and ET_PT and compared the calculated r_c to the constant r_c used to calculate ET_0 and ET_r during the mid-period. The ASCE parameterization to calculate atmospheric resistance (r_a) was used in the inverted PM equation. Days with available energy (net radiation (R_n) – ground heat flux (G)) of < 5 MJ day $^{-1}$ were excluded because low radiation values would result in extreme r_c values and to avoid including days with precipitation, which would bias the net radiation measurement of the NR-Lite2.

Once the discrepancies between reference and measured ET became apparent (see Sects. 3.2 and 3.3), we attempted two corrections to the ASCE reference ET approach to better parameterize sugarcane water use. One was a climatological correction to the ET coefficient ($K_\mathrm{C-adj}$). Following the FAO-56 approach (Allen et al., 1998), an adjustment term (K_adj) was calculated:

$$K_\mathrm{adj} = 0.04 * \left(U_\mathrm{2avg} - 2\right) - 0.004 * \left(\mathrm{RH}_\mathrm{avg} - 45\right) * h_\mathrm{avg}^{0.3}, \tag{4}$$

$$K_\mathrm{C-adj} = K_\mathrm{C-FAO} + K_\mathrm{adj}. \tag{5}$$

In Eqs. (4) and (5), $K_\mathrm{C-FAO}$ is the literature mid-canopy K_C value, U_2avg is mean location wind speed (m s^{-1}) at 2 m height, RH_avg is mean location relative humidity, and h_avg is average vegetation height. For our study we used average wind speed, relative humidity, and vegetation height over the mid-period to calculate these parameters in the absence of longer-term climate data. The FAO-56 provides a range of mid-period K_C values for sugarcane (1.25–1.40) for short reference ET. For adjustment, we chose the lowest end of the range (1.25) for $K_\mathrm{C-FAO}$ to enable the most conservative estimate of parameterized ET.

The second correction was to parameterize the ASCE–PM equation with a custom constant r_c. To estimate a r_c value, an intermediate bulk canopy resistance of 165 s m^{-1} was used, which was chosen as the weighted average of the r_c calculated by inverting the ET_PT at Windy and Lee. We then ran the full-form PM equation to calculate a new reference ET ($\mathrm{ET}_\mathrm{r-cane}$).

Along with corrections to the reference ET equations, we examined potential controls on the discrepancies between reference and measured ET values. Daytime and nighttime r_c were investigated by inverting the full PM equation with measured ET to see if there was a systematic time-of-day difference between the fields and to see if errors in daytime- or nighttime-parameterized r_c were disproportionally contributing to discrepancies in reference ET. Daily daytime and nighttime r_c were calculated for days that had at least eight (daytime) and four (nighttime) non-gap-filled half-hourly flux measurements. For these calculations, daytime was defined as $R_n > 50\,\mathrm{W\,m^{-2}}$ and nighttime as $R_n < -10\,\mathrm{W\,m^{-2}}$. We used this definition to avoid including periods with near zero Rn that would blow up the inverted PM equation. Finally, we evaluated the correlation between meteorological observations and discrepancies between the ASCE tall reference ET equation ($\mathrm{ET_r}$) and $\mathrm{ET_{EC}}$ to assess the importance of the advective and radiation terms in the PM equation.

2.4 Canopy cover and determination of mid-period

We measured fractional canopy cover with an optical camera to obtain an independent, conservative determination of the mid-season period (mid-period) for intercomparison of measured and reference ET. The mid-period is one of the growth/ET stages in the FAO/ASCE methodology and corresponds to maximum plant transpiration and the highest ecosystem coefficient ($K_{\mathrm{c-mid}}$). In unstressed sugarcane, the mid-period coefficient should exceed 1 (Allen et al., 1998), thus measured ET should exceed reference ET. The camera (TetraCam ADC multispectral camera, TetraCam Inc., Chatsworth, California, USA) contains a single precision 3.2 megapixel image sensor optimized for capturing green, red, and near-infrared wavebands of reflected light. A telescoping pole tripod system (GeoData Systems Management Inc., Berea, Ohio, USA) was used to suspend the camera directly above the plant at a height of 7 m and aim vertically downward at nadir view. Each field was photographed every $\sim 16 \pm 2$ days. Ten images were taken in two lines perpendicular to the irrigation line at pre-selected sampling locations in each field at solar noon ± 2 hours; sampling locations were identical throughout the study. Each image was preprocessed with image processing software (LView Pro 2006 – CoolMoom Corp., Hallandale, Florida, USA) to paint out the pixels of soil, grass, shadow, and other background. The preprocessed image was then analyzed using proprietary software (PixelWrench, TetraCam Inc.) to classify fractional vegetation cover based on threshold analysis, and the cover readings from the 10 locations were averaged to determine mean and standard error of field vegetation cover. We considered the beginning of the mid-period to be the latter of the beginning date of mid-period from the FAO-56 K_{C} curve (Allen et al., 1998) or the date when canopy cover clearly exceeded 80 %, which has been shown to coincide with the start of mid-period (Carr and Knox, 2011). The end of the $K_{\mathrm{C-mid}}$ period was set to 27 August 2012, which was the last date of irrigation data prior to the end of the FAO-56 mid-period. Finally, we further restricted the end of the mid-period in the earlier planted field (Lee) to ensure that the length of the mid-period was identical in both fields for intercomparison purposes.

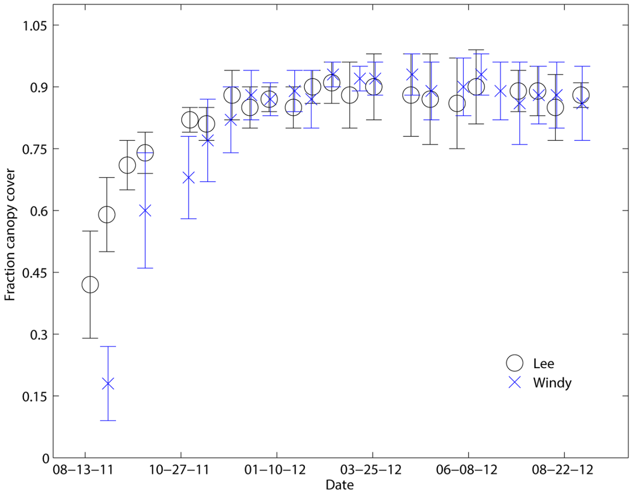

Figure 2. Measured mean and standard deviation of fractional vegetation cover from TetraCam for Windy and Lee fields.

2.5 LAI and stomatal resistance measurements

We measured LAI and leaf stomatal resistance in a field campaign during the mid-period for both EC fields (July 2012). LAI was measured using a nondestructive, optical plant canopy analyzer (LAI 2200, LI-COR Inc.) on 13 July in the Lee field and 16 July in the Windy field. At each of the 10 TetraCam sampling locations in each field (Sect. 2.4), we made 10 below-canopy and 5 above-canopy measurements with the optical canopy analyzer; we then used the manufacturer's software (FV2200, LI-COR Inc.) to determine mean and standard error of LAI for both fields. To observe leaf level stomatal resistance, we used a steady-state diffusion porometer (SC-1, Decagon Devices Inc.), which has been used to observe response to different irrigation regimes in multiple agronomic crops (e.g., Ballester et al., 2013; Hirich et al., 2014; Mabhaudhi et al., 2013; Mendez-Costabel et al., 2014). At each TetraCam point nine leaves were measured: three fully sunlit upper-canopy leaves near (< 20 vertical cm away from) the top visible dewlap (TVD) point (Glaz et al., 2008), three mid-level leaves that were attached to the cane stalk below the TVD height but were still mostly sunlit, and three lower canopy leaves that were partially to mostly shaded. Porometry measurements were made in a 30 s measurement window using the porometer's automatic mode. We also repeated the stomatal resistance measurements at five of the TetraCam points in the Windy field to evaluate the larger discrepancies in reference ET observed in that field.

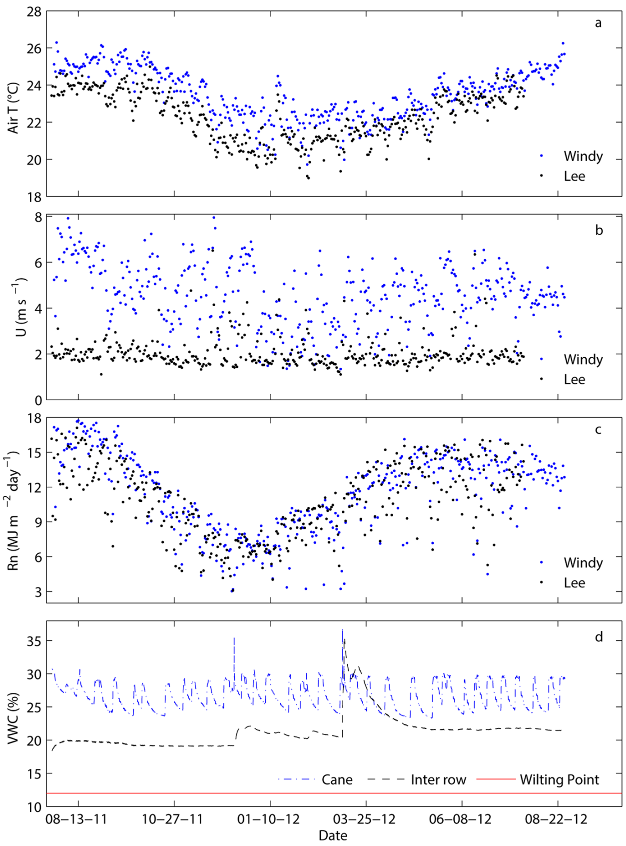

Figure 3. Meteorological and soil observations during the study period: **(a)** mean daily air temperature; **(b)** mean 24 h wind velocity; **(c)** cumulative daily net radiation; and **(d)** soil volumetric water content (VWC) data from Windy field at 20 cm depth underneath cane row (45 cm away from drip line) and inter-row or midway between drip lines (137 cm away from drip line). Wilting point noted as solid red line (12 % VWC).

3 Results

3.1 Fractional vegetation cover, LAI, and leaf stomatal resistance

Fractional vegetation cover increased rapidly in both fields after the beginning of the EC measurements (Fig. 2). Initial cover was < 20 % in Windy and < 45 % in Lee (112 and 142 days after planting (DAP), respectively). Some early TetraCam sampling dates were missed due to initial equipment failures. Vegetation cover exceeded 80 % in Lee on 3 November 2011 and 5 December 2011 in Windy (220 and 208 DAP, respectively), which we considered the onset of the mid-period. Both of these dates are later than the onset of mid-period according to the FAO-56 curve (180 DAP). Variation in cover was largest at the beginning of the study period (standard deviation of $\sim$ 10%) (Fig. 2). Vegetation cover was least variable near the onset of the mid-period (standard deviation < 5 %). Mean canopy height reached 3.97 m in Lee and 4.09 m in Windy by the end of the study.

Table 2. A summary of cumulative irrigation, rain, actual measured evapotranspiration-ET$_{\mathrm{EC}}$, and reference evapotranspiration values (ASCE short-ET$_0$ and tall-ET$_\mathrm{r}$, Priestley–Taylor ET$_{\mathrm{PT}}$, and a custom cane reference ET-ET$_{\mathrm{r-cane}}$) for the entire study period and the mid-period. All values are in mm.

	Lee		Windy	
	Whole study	Mid-period	Whole study	Mid-period
Irrigation	1599	1348	1928	1221
Rain	58	58	140	122
ET$_{\mathrm{EC}}$	1191	843	1389	1001
ET$_0$	1487	1042	2099	1367
ET$_\mathrm{r}$	1828	1292	2861	1861
ET$_{\mathrm{PT}}$	1470	1008	1707	1096
ET$_{\mathrm{r-cane}}$	1317	947	1662	1128

Mean ± standard error of measured LAI was 4.9 ± 0.2 in Windy on 13 July 2012 and 4.7 ± 0.3 in Lee on 16 July 2012. Midday leaf stomatal resistance (r_s) observations of fully sunlit leaves in Windy ($n = 32$) and Lee ($n = 21$) showed substantial variation, ranging from 45 to 259 s m^{-1} in Windy and 40 to 640 s m^{-1} in Lee. Median r_s in Windy and Lee were 112 and 114 s m^{-1}, respectively. Mean ± standard deviations of r_s in Windy and Lee were 125 ± 57 s m^{-1} and 161 ± 157 s m^{-1}, respectively. There were two observations in Lee of sunlit stomatal resistance of > 500 s m^{-1}. Excluding these two observations resulted in a revised mean and median r_s in Lee of 114 and 104 s m^{-1}, respectively. Mean sunlit stomatal resistance was not significantly different ($p < 0.01$) from 100 s m^{-1} in either Windy ($p = 0.02$) or Lee ($p = 0.09$).

3.2 Meteorological observations

Air temperature and net radiation were similar in both Windy and Lee (Fig. 3a and c; Table 1). In Windy, mean daily air temperature ranged from 19.0 to 25.0 °C over the study period, whereas in Lee, mean daily air temperature ranged from 19.7 to 26.3 °C. Mean air temperature was higher in Windy than Lee (23.5 and 22.3 °C, respectively) with a similar, low day-to-day variability (standard deviation of 1.3 °C for both fields). Daily net radiation (Rn) was also similar between fields; Rn was slightly higher in Windy versus Lee (11.5 and 10.9 MJ m^{-2} day^{-1}; Fig. 3c and Table 1). Both fields showed larger relative variations in R_n ($\sim$ 10 MJ m^{-2} day^{-1}) than in other meteorological observations. Wind velocities were sharply divergent between the two fields. Mean wind velocity was more than twice as high (4.6 m s^{-1} versus 2.0 m s^{-1}) in Windy compared to Lee (Fig. 3b; Table 1). Wind velocities were also more variable in Windy than Lee (standard deviation of 1.4 and 0.7 m s^{-1}, respectively).

VWC observations in the Windy field underneath the sugar cane row/line varied from 23 to 30 % during the mid-

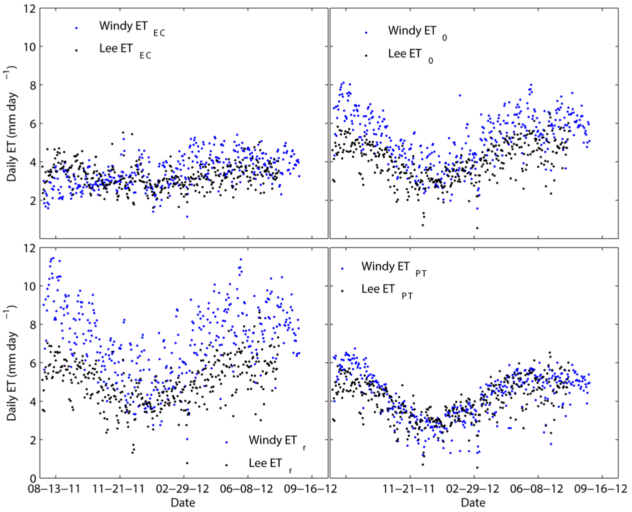

Figure 4. Daily measured and reference ETs for EC tower fields from the tower's establishment until the end of the study period for each field.

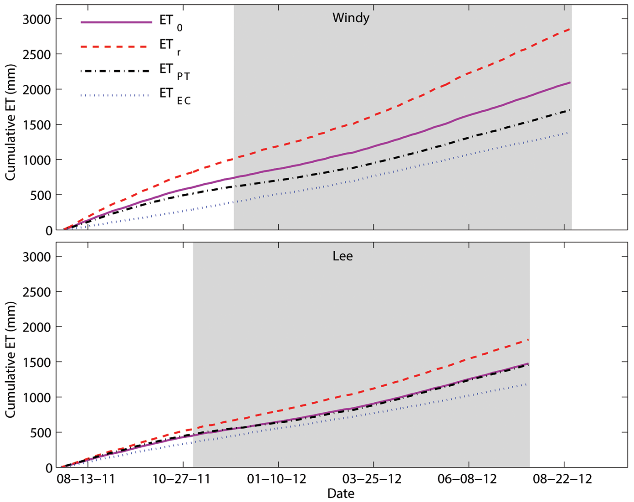

Figure 5. Cumulative measured and reference ET for Windy and Lee. Shaded background indicates mid-period when ground canopy cover exceeded 80 %.

period except after major rain events in December 2011 and March 2012 when they spiked to 36–37 % (Fig. 3d). At all times, VWC remained well above wilting point (12 %) for both sensors (Table 1). Available plant water in the top 40 cm of the soil at minimum VWC was ∼ 40 mm. Soil matric potentials in Windy near typical maximum (30 %) and minimum (24 %) soil VWC were −0.01 and −0.033 MPa, respectively (Table 1). Shallow VWC observations underneath the cane row are likely indicative of plant water stress due to the majority of drip-irrigated Hawaiian sugarcane roots being at less than 50 cm depth (Evensen et al., 1997). VWC observations between drip lines showed relatively little periodicity compared to underneath the cane row, indicating that neither irrigation events nor root depletion was impacting VWC at this location. Due to difficulties with instrument installation and instrument failure we were not able to obtain a reliable time series of soil VWC observations in the Lee field. Precipitation at both fields was less than 150 mm over the course of the study, with irrigation providing more than 90 % of the water input (Table 2).

From the tower's establishment until the end of the study period, daily EC measured ET (ET_{EC}) ranged from 1.6 to 5.5 mm day^{-1} with a mean of 3.2 mm day^{-1} in Lee and 1.6 to 5.5 mm day^{-1} with a mean 3.8 mm day^{-1} in Windy (Fig. 4). ET_{EC} showed relatively little seasonal variation (< 3 mm day^{-1} from summer maxima to winter minima) and greater day-to-day variations of 1–2 mm day^{-1}. Cumulatively, mid-period ET_{EC} was 158 mm higher in Windy than in Lee (Fig. 5; Table 2). Factors contributing to higher ET_{EC} in Windy include higher wind speed, slightly higher Rn, a higher mean air temperature, and lower mean daily relative humidity. However, maximum daily air temperature is higher near Lee than Windy. Ground heat flux was minimal (< 3 % of R_n during daytime periods) at both sites during the mid-period.

Quality control checks on the EC data indicated no significant issues with ET measurements. Energy closure varied significantly between the sites, with daily energy closure of the turbulent fluxes of 75 % at Lee and 97 % at Windy. As data processing and instrumentation were identical between sites, the difference in energy closure is very likely due to the differences in topography and turbulence between the two fields, particularly nighttime turbulence (Anderson and Wang, 2014). Friction velocity at Windy rarely dropped below the critical threshold (0.1 m s^{-1}) at night (2.5 % of the half-hourly fluxes). Mean 90 % footprint lengths during the study period, determined following Kljun et al. (2004), were 158 m in Windy and 124 m in Lee, which indicate that our EC towers were observing the field of interest even during the rare periods (∼ 7 % of record) when we were observing in the short fetch direction (Table 1), such as during Kona winds (winds from the south and west). During the predominant trade wind flows (prevailing winds from the northeast), our fetch in both fields was > 200 m.

3.3 Reference ET at EC tower sites

Daily short (ET_0) and tall (ET_r) ASCE reference ET were significantly different between the two sites (Fig. 4). In Windy, ET_0 ranged from 1.6 to 8.1 mm day^{-1} over the study period with a mean of 5.2 mm day^{-1} (5.1 mm day^{-1} over the mid-period). ET_r ranged from 2.0 to 12.3 mm day^{-1} with a mean of 7.14 mm day^{-1} (7.0 mm day^{-1} for mid-period). For Lee, ET_0 varied from 0.6 to 6.5 mm day^{-1} with a mean of 4.0 mm day^{-1} (3.9 mm day^{-1} for mid-period). ET_r ranged from 0.8 to 8.6 mm day^{-1} with a mean of 5.0 mm day^{-1} (4.8 mm day^{-1} mid-period). The PT ET (ET_{PT}) showed less

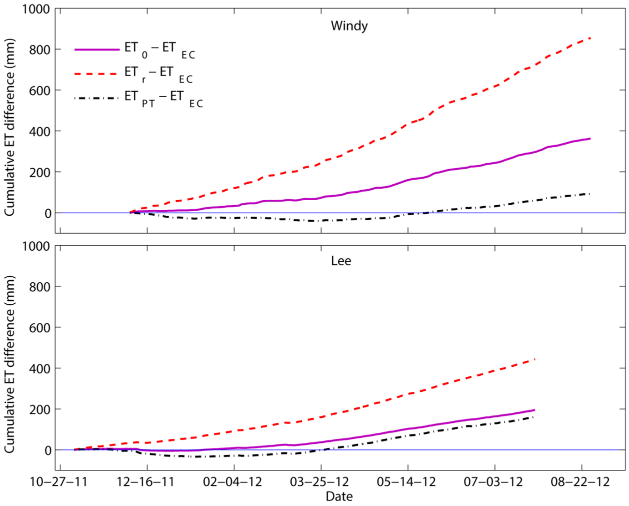

Figure 6. Cumulative difference between reference and measured ET since the beginning of the mid-period in each EC tower field.

difference between the two fields. Mean ET_{PT} was slightly higher at Windy (4.3 and 4.1 mm day^{-1} mid-period) than at Lee (4.0 and 3.8 mm day^{-1} mid-period).

Over the course of the study, the cumulative ET_0 in Windy was 612 mm higher than in Lee, and cumulative ETr was 1032 mm higher (Fig. 5; Table 2). Similar to the daily values, cumulative ET_{PT} values were considerably closer, with Windy exceeding Lee by 237 mm. As expected, the cumulative difference between reference equations and ET_{EC} grew in the early portion of the study period prior to the mid-period (Fig. 5). During the mid-period, the difference between ET_r and ET_{EC} grew significantly larger in both EC fields. Windy also saw increasing differences between ET_0, ET_{PT}, and ET_{EC}, whereas in Lee, cumulative ET_0 and ET_{PT} tracked quite closely with each other.

To further evaluate these discrepancies between reference and ET_{EC}, we calculated the cumulative difference between the three reference ET equations and ET_{EC} during the mid-period (Fig. 6). ET_{PT} was the only equation with near zero cumulative difference for a substantial amount of the mid-period for both fields; ET_0 was near 0 for the Lee field from October 2011 to February 2012 but not for the Windy field. Over the mid-period in Windy, the difference between cumulative ET_{EC} and ET_{PT} ranged from −40 mm in March 2012 to 92 mm at the end of the study period (August 2012) with cumulative differences of < 40 mm until July 2012. In Lee, the differences were greater, varying between −33 and 161 mm. The difference with ET_0 ranged from 0 (at the beginning of mid-period) to 362 and 195 mm in Windy and Lee, respectively. ET_r showed the greatest cumulative differences of 854 and 443 mm in Windy and Lee.

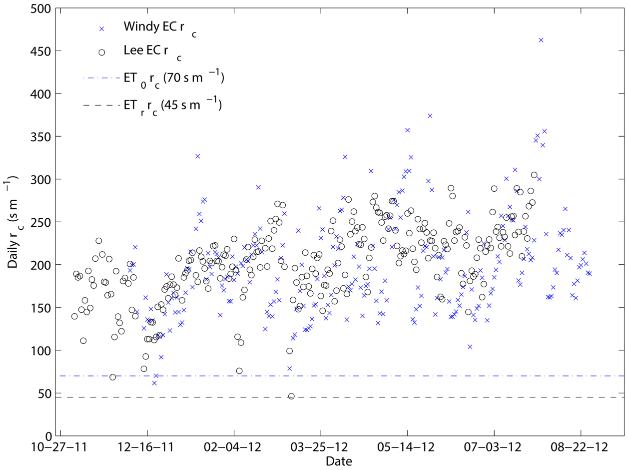

Figure 7. Calculated daily bulk canopy resistance at Windy and Lee from the EC towers for the mid-period. Dotted lines show daily time step resistances from short-canopy (ET_0 – 70 s m^{-1}) and tall-canopy (ET_r – 50 s m^{-1}) reference surfaces.

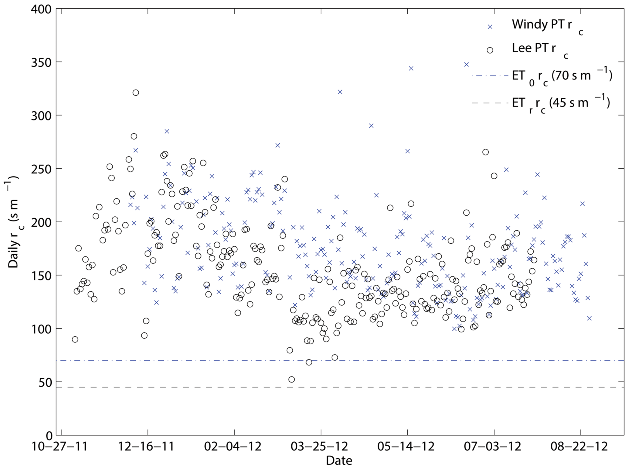

Figure 8. Calculated daily bulk canopy resistances at Windy and Lee from inverting the Priestley–Taylor (PT) ET for the mid-period. Dotted lines again show daily time step resistances from short and tall canopy for comparison.

3.4 Bulk canopy resistances at EC towers, soil observations, and patterns in ET discrepancies

r_c varied considerably between Windy and Lee for ET_{EC}. For the mid-period, mean ± standard deviations of daily r_c at Lee and Windy were 201 ± 47 and 145 ± 36 s m^{-1}, respectively (Fig. 7). With respect to ET_{PT}, mean ± standard deviations of daily r_c at Lee and Windy during the mid-period were 146 ± 28 s m^{-1} and 175 ± 42 s m^{-1}, respectively (Fig. 8). In all cases, mean r_c values were significantly higher (> 75 s m^{-1}) than the daily r_c values used to parameterize the ET_0 and ET_r equations.

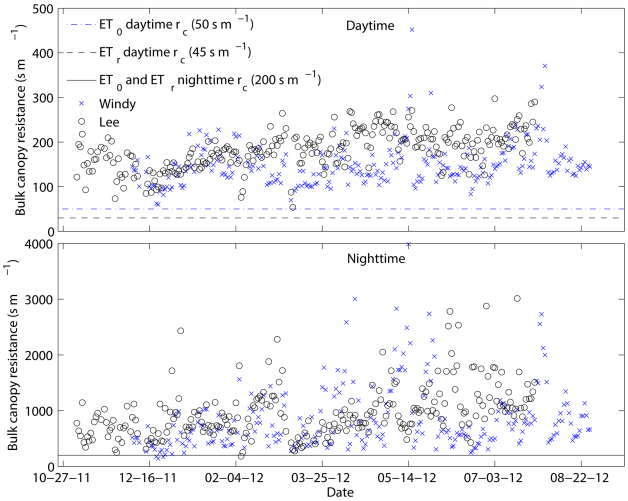

Figure 9. Calculated mean nighttime and daytime bulk canopy resistances (following Fig. 6) compared to assumed resistances.

Daily daytime and nighttime r_c are shown in Fig. 9. Nighttime r_c shows greater difference between towers, with mean ± standard deviation in Windy and Lee of 675 ± 289 and $808 \pm 445\,\mathrm{s\,m^{-1}}$ and substantially larger absolute and relative standard deviation in r_c. For both fields, daytime and nighttime r_c were larger than the ASCE r_c parameterizations for almost all days. One other notable feature of the resistance terms was the low atmospheric resistance (r_a); in Windy and Lee, mean daily r_a were 17.7 and $38.6\,\mathrm{s\,m^{-1}}$, respectively, over the study period.

With respect to meteorological controls on the discrepancies between $\mathrm{ET_r}$ and $\mathrm{ET_{EC}}$, the only parameter that was highly correlated to ET discrepancy ($\mathrm{ET_r}$-$\mathrm{ET_{EC}}$) was VPD with a coefficient of determination (r^2) of 0.66 (Fig. 10a). VPD showed a much stronger correlation with ET discrepancy than $\mathrm{ET_{EC}}$ ($r^2 = 0.19$) (Fig. 10b). Available energy was moderately correlated with ET discrepancy ($r^2 = 0.37$) while all other tested parameters (daily minimum, mean and maximum wind speed and temperature) had weak or no correlation with ET discrepancy ($r^2 < 0.1$).

3.5 Corrections to better parameterize sugarcane water use

The climatological K_C adjustment (K_{adj}) had relatively little impact on calculated water use. In the Windy field K_{adj} was −0.0126, and in Lee K_{adj} was −0.0359. For both fields, the wind adjustment offset the relative humidity/vegetation height adjustment as all three parameters were greater than zero. The magnitude of the K_{adj} term was insufficient to account for the observed discrepancies between reference ET and $\mathrm{ET_{EC}}$.

Cumulative differences between $\mathrm{ET_{r-cane}}$ and $\mathrm{ET_{EC}}$ are shown in Fig. 11 along with the differences between $\mathrm{ET_{PT}}$ and $\mathrm{ET_{EC}}$. $\mathrm{ET_{r-cane}}$ showed some improvements over $\mathrm{ET_{PT}}$ in predicting measured ET between October 2011 and March 2012; in particular $\mathrm{ET_{r-cane}}$ had less underestimation of ET (15 to 27 mm improvement) in winter and spring for both fields and had consistently better performance in the Lee field. $\mathrm{ET_{r-cane}}$ had worse performance than $\mathrm{ET_{PT}}$ during the summer in the Windy field (40 mm). The minimum cumulative difference between $\mathrm{ET_{r-cane}}$ and $\mathrm{ET_{EC}}$ was −12 and −18 mm in Windy and Lee, respectively. The maximum cumulative difference between $\mathrm{ET_{r-cane}}$ and $\mathrm{ET_{EC}}$ was 132 and 164 mm at the end of the study period in Windy and Lee, respectively.

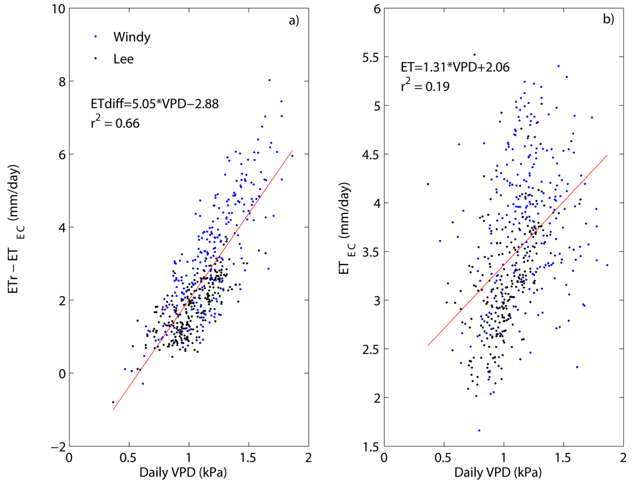

Figure 10. (a) Relationship between daily ET discrepancy ($\mathrm{ET_r}$-$\mathrm{ET_{EC}}$) and daily vapor pressure deficit (VPD) from the beginning of the mid-period to the end of the study period. Regression equation is fitted to the entire pool of data from Lee and Windy. **(b)** Relationship between measured ET and daily VPD; time period and regression approach are the same as in **(a)**.

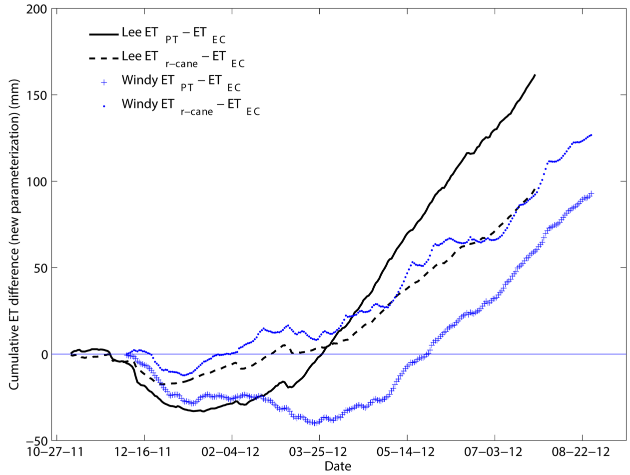

Figure 11. Cumulative difference between new reference ET (custom bulk canopy resistance of $165\,\mathrm{s\,m^{-1}}$) and measured ET for both EC tower fields during the mid-period.

4 Discussion

4.1 Is Hawaiian sugarcane representative of a fully transpiring reference ET surface?

Well-irrigated, full-canopy sugarcane has generally been reported to have an ET rate 1.1 to 1.4 times the ASCE/FAO-56 reference ET_0 equation (Da Silva et al., 2012; Inman-Bamber and McGlinchey, 2003), and rain-fed sugarcane has been reported to have an ET rate approaching ET_0 (Cabral et al., 2012). Furthermore, a reference PM–ET equation designed specifically for sugarcane, created by McGlinchey and Inman-Bamber (1996), has a bulk canopy resistance that is slightly lower than the daily ASCE ET_r equation (40 versus $45\,\mathrm{s\,m^{-1}}$ for ASCE ET_r). Therefore, the significant overestimation of measured ET (ET_{EC}) by the ET_0 and ET_r equations found in this study was quite surprising. Although Windy and Lee fields had slight differences in planting dates, available soil water capacity, and fetch (Table 1), we do not believe these account for the observed ET/reference ET differences between the fields. Seasonal variation in temperature in Hawaii is quite small; wind speeds appeared to be uncorrelated to seasonality. Wind fields in central Maui are generally very strong, and our separate calculations of reference ET using independent farm weather station observations (Supplement S1) and publicly available airport weather data from Kahului airport (http://mesonet.agron.iastate.edu/request/download.phtml?networkHI_ASOS – station ID PHOG) show higher-than-typical values of reference ET for a tropical region.

The quality of EC observations was good, especially at the Windy tower where high turbulence, flux footprints that were well within field boundaries, low proportion of time periods requiring gap filling, and excellent energy budget closure ($H + \mathrm{LE}$ was $> 95\,\%$ of daily R_n-G) indicated that the methodological requirements of the EC method were well satisfied (Anderson and Wang, 2014). At the Lee tower, EC measurements showed a more typical pattern, with a larger number of gaps during still nighttime periods when ET is low. Furthermore, seasonal and annual totals of ET have been shown to be relatively insensitive to gap-filling methodologies (Alavi et al., 2006). Finally, while the gap-filling method of Reichstein et al. (2005) may systematically underestimate wet canopy evaporation due to exclusion of all EC periods during and immediately after rain, this bias is likely to be insignificant at our sites due to the low precipitation (Table 2) and drip irrigation that would minimize wetting of the leaves.

One hypothesis is that portions of the fields measured by our EC towers were under significant water stress or had less-than-optimal cover and thus were not representative of a reference ET type surface. Uniformity of irrigation is a major concern with drip irrigation, particularly with sub- and near-surface drip lines where root development can plug or pinch drip lines, leading to insufficient irrigation (e.g., Soopramanien et al., 1990). At our field with higher ET (Windy), visible dry lines arising from pinched drip tubes appeared in parts of the field at and after the end of the study period. However, there are multiple independent lines of evidence against this hypothesis.

With respect to canopy cover, the TetraCam observations of cover (Fig. 2) show that fractional cover remained above 80 %, a threshold for the mid-period K_C (Carr and Knox, 2011; Inman-Bamber and McGlinchey, 2003). More evidence for full canopy comes from the LAI measurements made in July 2012 toward the end of the mid-period. In both Lee and Windy, mean LAI (4.7 and 4.9) were slightly higher than the LAI (4.5) parameterized in the ET_r equation (Allen et al., 2005). These two types of data indicate that incomplete cover is not an issue with our study sites.

Another possibility is that the sugarcane leaves are under significant water stress and thus are transpiring at a lower rate. Four factors show that the sugarcane is unlikely to be water stressed. First, porometer measurements from the July 2012 campaign of midday, sunlit leaf stomatal resistance were not significantly $> 100\,\mathrm{s\,m^{-1}}$. The $100\,\mathrm{s\,m^{-1}}$ comes from the mean leaf level stomatal resistance of a sunlit leaf on a well-watered plant, as measured by Szeicz and Long (1969), and which is used as a basis for scaling bulk canopy resistance in the ASCE and FAO-56 approaches (Allen et al., 1998, 2005). Second, we compared the daily observed ET coefficient (K_C) from the day immediately preceding a substantial irrigation or rain event (defined as $> 8\,\mathrm{mm\,day^{-1}}$) during the mid-period with daily K_C 2 and 3 days after the irrigation event using a paired t test ($n = 106$ in Windy and $n = 98$ in Lee). We reasoned that stressed full-canopy sugarcane would respond to irrigation within 3 days, but that 3 days were short enough to avoid confounding changes due to variations in field water budgets. Neither field showed significantly greater daily ET_{EC} following an irrigation during the mid-period ($p > 0.40$ for all tests). Third, the soil VWC data from the Windy field indicate relatively high soil moisture content; available soil water underneath the cane row in the middle of the root zone always remained at $> 50\,\%$ of available capacity. Windy's soils were also near field capacity (and far above permanent wilting point) based on matric potential at typical maximum and minimum soil VWC (Table 1). The VWC content also argues against severe water stress that might persist after irrigation relieves the soil moisture deficit; thus if the ASCE reference ET equations and coefficients were applicable to this situation, we should see at least some days with ET_{EC} in the range of ET_0 and ET_r (6–10 $\mathrm{mm\,day^{-1}}$ in Windy) when soil moisture was near or above field capacity. Fourth, measured irrigation plus precipitation as recorded by the plantation was compared to measured cumulative ET_{EC}, with cumulative mid-period irrigation and precipitation exceeding ET_{EC} by 342 mm in Windy (Table 2). At all times in the Windy field, cumulative ET_{EC} was significantly less than irrigation plus precipitation. In Lee, by early January 2012 cumulative precipitation and irrigation exceeded ET_{EC}; by the end of the mid-period (July 2012), cumulative irrigation and precipitation exceeded cumulative $\mathrm{ET_{EC}}$ by $> 500\,\mathrm{mm}$ (Table 2). In summary, the evidence of full canopy and the lack of evidence of water stress indicated that the mid-period sugarcane at our study fields should be fully transpiring.

4.2 Why do the standardized ASCE reference ET equations differ between similar sites?

Without clear evidence of water stress or lack of canopy cover over the study sites, we examine some explanations for the overestimation of the ASCE $\mathrm{ET_0}$ and $\mathrm{ET_r}$ compared to $\mathrm{ET_{EC}}$ and $\mathrm{ET_{PT}}$. Four hypotheses include (1) scaling of leaf level stomatal resistance to whole canopy bulk resistance, (2) incorrect parameterization of daytime leaf level resistance, (3) underestimation of nighttime bulk canopy resistance, and (4) underestimation of atmospheric resistance. Scaling up leaf level resistance measurements has long been recognized as a major challenge (Bailey and Davies, 1981; Furon et al., 2007; Sprintsin et al., 2012) due to heterogeneity of environmental variables. The ASCE/FAO reference ET methods take a single layer "big leaf" approach to scaling to convert non-stressed leaf resistances (r_s) into whole canopy bulk resistances (r_c) by using an "effective LAI" where r_c is calculated by dividing r_s by effective LAI. ASCE assumes that effective LAI is equivalent to 0.5 times measured LAI, which is assumed to be 2.9 for $\mathrm{ET_0}$ and 4.5 for $\mathrm{ET_r}$, thus resulting in effective LAIs of 1.4 and 2.3, respectively. Studies of well-watered crops have found effective LAIs which vary quite significantly from those assumed for the reference surface. Tolk et al. (1996) found an effective LAI of 1.3 for irrigated maize in Texas that was only 30 % of the maximum measured LAI. Other studies (Alfieri et al., 2008; Mehrez et al., 1992) have assumed effective LAI as a linear function of LAI, with effective LAI equaling 50 % of LAI when LAI is 6. Ultimately, the effective LAI concept is only a presumed distribution of leaves with differing r_s (Bailey and Davies, 1981); there is a possibility that the relatively unique production system in our study fields results in a different, distinctive leaf distribution with a lower effective LAI. Along with effective LAI, another leaf parameter that could be different is leaf level resistance (r_s). Although we did not find a highly significant difference between measured r_s and the r_s assumed in the ASCE parameterizations ($100\,\mathrm{s\,m^{-1}}$), we were able to measure r_s in only one field campaign during the mid-period, where r_s observations were limited by clouds and other logistical limitations. A large number of r_s observations are needed to accurately characterize r_c (Denmead, 1984); more than we could feasibly measure during our field campaign. We also note that other researchers (e.g., Zhang et al., 2008) have found non-stressed r_s values greater than $100\,\mathrm{s\,m^{-1}}$.

Two other nonbiological factors could help explain the discrepancy between ASCE reference and mid-period $\mathrm{ET_{EC}}$. One is nighttime r_c. Both ASCE approaches assume a nighttime r_c of $200\,\mathrm{s\,m^{-1}}$, which is based on measurements of damp soil beneath a grass lysimeter (Allen et al., 2006). Measured nighttime r_c at our fields was significantly higher. We suspect that the taller sugarcane canopy and substantial layer of trash and lodged cane minimizes bare soil water evaporation, thus increasing nighttime r_c. Oliver and Singels (2012) found a significant decrease in soil evaporation in sugarcane with surfaces covered by crop residue. Furthermore, the minimal daytime ground heat flux ($< 5\,\%$) further reduces nighttime ET. Another factor is the canopy energy storage that is considerable in high-biomass systems (Anderson and Wang, 2014). Finally, we note that nighttime r_c is likely to be a locally specific value; $200\,\mathrm{s\,m^{-1}}$ is too low for our study region but too high for other regions with significant advection (Evett et al., 2012).

Along with nighttime r_c, we examined the role of atmospheric resistance (r_a) in parameterizing ET, given the low observed mean r_a at Windy ($< 20\,\mathrm{s\,m^{-1}}$) and the demonstrated importance of atmospheric resistance/conductance parameterizations in coastal tropical regions for accurate ET parameterization (e.g., Holwerda et al., 2012). Given the canopy architecture of mid-period sugarcane in our study fields, we were not certain about the equations that are commonly used to parameterize zero plane displacement height and roughness lengths, which are also used in the ASCE reference ET equations. To test the effect of r_a uncertainty, a sensitivity analysis was conducted. We used r_a that was 200 and 50 % of the original r_a and recalculated r_c for both EC towers. In all cases, the new r_a changed the r_c values by $< 10\,\mathrm{s\,m^{-1}}$, with most r_c values changed by $< 5\,\mathrm{s\,m^{-1}}$. These values are too small to explain the discrepancy between observed and parameterized r_c. The presence of r_a in both the numerator and denominator of the PM equation limits the impact of variation in r_a on r_c.

Finally, we note that the ASCE and FAO reference ET and PT ET equations show varying sensitivity to meteorological variables depending upon climate. Multiple studies have shown spatial, seasonal, and interannual variation in the sensitivity of reference ET to meteorological inputs, with the most sensitive input (air temperature, wind velocity, relative humidity, etc.) changing depending upon season and location (e.g., Bandyopadhyay et al., 2009; Estévez et al., 2009; Gong et al., 2006; Huo et al., 2013; Irmak et al., 2006; Liang et al., 2008; Liu et al., 2014). Irmak et al. (2006) and Estévez et al. (2009) found increased sensitivity to reference ET parameterization at locations with higher wind velocities in the United States and Spain, respectively. Bandyopadhyay et al. (2009) and Huo et al. (2013) reported that decreased wind velocities accounted for the largest proportion of decreased reference ET in climatically differing regions in India and China. Across a large river basin in China (Chiang Jiang), Gong et al. (2006) showed that sensitivities of reference ET to other meteorological variables (air temperature and relative humidity) depended significantly on the spatial pattern of wind sensitivity. With respect to the PT equation, variability in the PT coefficient (α) has been found at lower to middle LAI (LAI less than 3) depending upon the soil wetness and covering (Ding et al., 2013). This may be particularly relevant for our system in early growth stages with fractional soil wetness and partial cover from sugarcane detritus (trash). Conversely, at mid- to full canopy (LAI greater than 3) or when soil moisture was greater than 50 % of the available field capacity, α showed little sensitivity.

5 Summary and conclusion

We investigated discrepancies between two standardized reference ET equations and EC-measured ET at two field sites over irrigated sugarcane on Maui. At both fields, measured daily ET during the mid-period should have approached the tall reference ET equation and exceeded the short reference ET equation. At both fields, both ASCE reference ET equations significantly overestimated mid-period ET compared to EC observations of ET. The PT equation performed substantially better at the Windy field than the short reference ET, while the short reference ET equation and PT were more closely matched at the Lee field. We used a custom bulk canopy resistance derived from inverting PT ET; the custom cane reference ET equation had less seasonal variation in ET discrepancy. Multiple independent field observations did not indicate insufficient canopy cover or plant water stress reducing $\mathrm{ET_{EC}}$ significantly.

This study indicated nighttime bulk canopy resistance, leaf stomatal resistance, and effective LAI as possible causes for the discrepancy in bulk canopy resistance (and reference ET estimates) between the ASCE reference equations and mid-period $\mathrm{ET_{EC}}$. The higher bulk canopy resistances and relationship between ET discrepancies and vapor pressure deficit indicated that the ASCE equations overestimated the advective component of ET. Ultimately, validation with field methods, including micrometeorology and water balance methods, is needed to establish the accuracy of the ASCE equations in a region where they have not been tested previously. Adjusting the bulk canopy resistance to local climate to reduce the advective component of ET may make the full ASCE PM equation a more appropriate equation in this region.

The PT equation performs better than $\mathrm{ET_r}$ or $\mathrm{ET_0}$ in our study region. The PT equation likely provides a more robust estimation of reference ET in regions with high humidity. The simplicity of the PT equation also makes it attractive for use in larger scale project planning as it has been parameterized in satellite-based ET models (e.g., Choi et al., 2011; Jin et al., 2011) and can be used in regions with a relative paucity of surface meteorological data, unlike the ASCE/FAO equations that require near-surface wind speed and humidity data, which are currently supplied by surface meteorological stations and interpolated in satellite-based approaches (Allen et al., 2007; Hart et al., 2009).

The results illustrate the importance of the careful use of reference ET equations and coefficients for assessing actual ET in hydrologic applications. Our finding of high bulk canopy resistance and low atmospheric resistance supports Widmoser's (2009) recommendation for research of the canopy resistance/atmospheric resistance ratio. Many areas with changing hydrology (Elison Timm et al., 2011) and areas that currently and may soon use irrigation in previously non-irrigated fields (Baker et al., 2012; Salazar et al., 2012) are outside of the semi-arid areas where reference ET methods have been primarily developed and tested. As such, it will be important to ensure that the appropriate reference equation is used to parameterize evaporative demand.

The Supplement related to this article is available online at doi:10.5194/hess-12-583-2015-supplement.

Acknowledgements. We thank Ilja van Meerveld, Lixin Wang, Maarten Waterloo, and two anonymous reviewers for their constructive feedback on this manuscript. Don Schukraft discussed previous meteorological investigations and observations at the farm. Jim Gartung, ARS-Parlier, assisted with the establishment of the EC tower and TetraCam measurements. David Grantz provided insight into the historical evaluation of ET data for Hawaiian sugarcane. Adel Youkhana, Neil Abranyi, Jason Drogowski, and the farm crew assisted with data collection and field logistical support. This research was supported by USDA Agricultural Research Service, national program 211: Water Availability and Watershed Management and by the US Navy, Office of Naval Research. Note: the US Department of Agriculture (USDA) prohibits discrimination in all its programs and activities on the basis of race, color, national origin, age, disability, and where applicable, sex, marital status, familial status, parental status, religion, sexual orientation, genetic information, political beliefs, reprisal, or because all or part of an individual's income is derived from any public assistance program (not all prohibited bases apply to all programs.) Persons with disabilities who require alternative means of communication of program information (Braille, large print, audiotape, etc.) should contact USDA's TARGET Center at (202) 720-2600 (voice and TDD). To file a complaint of discrimination, write to USDA, Director, Office of Civil Rights, 1400 Independence Avenue, S.W., Washington, D.C. 20250-9410, or call (800) 795-3272 (voice) or (202) 720-6382 (TDD). USDA is an equal opportunity provider and employer.

Edited by: L. Wang

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