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Evapotranspiration rates and crop coefficients for a restored marsh in the Sacramento–San Joaquin Delta, California, USA†

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Abstract:

The surface renewal method was used to estimate evapotranspiration (ET) for a restored marsh on Twitchell Island in the Sacramento–San Joaquin Delta, California, USA. ET estimates for the marsh, together with reference ET measurements from a nearby climate station, were used to determine crop coefficients over a 3-year period during the growing season. The mean ET rate for the study period was 6 mm day^{-1}, which is high compared with other marshes with similar vegetation. High ET rates at the marsh may be due to the windy, semi-arid Mediterranean climate of the region, and the permanently flooded nature of the marsh, which results in very low surface resistance of the vegetation. Crop coefficient (K_c) values for the marsh ranged from 0·73 to 1·18. The mean K_c value over the entire study period was 0·95. The daily K_c values for any given month varied from year to year, and the standard deviation of daily K_c values varied between months. Although several climate variables were undoubtedly responsible for this variation, our analysis revealed that wind direction and the temperature of standing water in the wetland were of particular importance in determining ET rates and K_c values. Published in 2007 by John Wiley & Sons, Ltd.

KEY WORDS crop coefficient; evapotranspiration; K_c value; marsh; Sacramento–San Joaquin Delta; *Schoenoplectus acutus*; surface renewal method; *Typha*

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INTRODUCTION

Although not widespread in arid or semi-arid regions, wetlands are often found along stream banks (i.e. riparian systems), lake margins (i.e. marshes), and in groundwater discharge areas (i.e. wet meadows and fens). In addition, wetlands may also form as seasonal pools or ponds, showing great activity after a wet season and then becoming dormant during dry months (i.e. endorreic pans, prairie potholes, vernal pools). In temperate to tropical latitudes, wetlands in arid or seasonally arid areas often have high rates of evapotranspiration (ET) due to warm growing seasons and the influence of air advection. These high rates of ET comprise the largest hydrologic outflow in the water budget of such wetlands. For this reason, particularly in arid areas, accurate estimates of ET are crucial for proper water management of existing wetlands and successful wetland restoration and creation projects.

As a whole, wetlands in arid and semi-arid regions have been poorly studied, and the topic of ET is no exception. Only a few good ET estimates exist for such 'arid wetlands' (e.g. Allen *et al*., 1994; Allen, 1998; Bidlake, 2000), yet they rarely span more than a few weeks in the summer and have only been made for a few common plant surfaces. Choosing the right technique for measuring ET in arid wetlands may be especially challenging due to the particular shape (e.g. a long, narrow riparian corridor) or the geographic position of wetlands (e.g. an oasis in a desert) that makes them prone to strong advective forces. Of the variety of techniques available for measuring ET, the micrometeorological techniques such as the Bowen ratio energy method, eddy covariance, and light detection and ranging (LIDAR) have shown success when applied to arid wetlands (Allen *et al*., 1994; Cooper *et al*., 1998, 2002; Bidlake, 2000; Eichinger *et al*., 2000). Yet, in applying these approaches, researchers must take painstaking care to meet each of the underlying assumptions and overcome remaining technical issues. In the Bowen ratio, the assumption of adequate fetch can be troublesome because wetlands may not be large enough to meet the fetch requirement over uniform vegetation (Monteith and Unsworth, 1990). Fetch may also be an issue with eddy covariance, and the challenge of purchasing and then maintaining expensive and complex instrumentation, such as an infrared gas analyser, may be burdensome. With LIDAR the prohibitive price of about US$1 000 000 may preclude application (Drexler *et al*., 2004). The challenge, therefore, is to choose a technique of measuring ET that best suits the particular wetland under study, yet which is still feasible with respect to cost and technical expertise (Drexler *et al*., 2004).

The surface renewal technique has thus far not been widely used, but it has shown great promise in an

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endorreic lagoon (Zapata and Martinez-Cob, 2001), in grass, wheat and sorghum canopies (Snyder *et al.*, 1996; Spano *et al.*, 1997a and b), and in grape vineyards (Spano *et al.*, 2000). The particular benefits of the surface renewal technique are the low cost, easy application, and the small footprint, which translates into a small fetch requirement. This allows for making ET measurements in small patches with uniform vegetation. The basic premise of the surface renewal technique is that air near a surface is replaced by ambient air from above. The method is not based on flux gradient theory, but instead depends mainly on nearly vertical transport of air parcels, which lessens the importance of fetch. Statistical analysis is used to estimate the amplitude and duration of rapid air temperature increases and decreases (ramps) at the surface (Gao *et al.*, 1989; Paw U *et al.*, 1995). The latent heat flux density (LE), is determined as the residual of the energy budget equation:

$$\mathrm{LE} = R_\mathrm{n} - G - H \quad (\mathrm{W\ m^{-2}}) \qquad (1)$$

where R_n is the net radiation, H is the sensible heat flux density and G is the heat flux transfer to and from the soil and water. In the surface renewal method, G and R_n are measured according to standard micrometeorological techniques (Drexler *et al.*, 2004), but H is determined according to the following equation (Gao *et al.*, 1989; Paw U *et al.*, 1995):

$$H = \alpha H' = \alpha \left[\rho C_p \left(\frac{a}{d+s}\right) z\right] \quad (\mathrm{W\ m^{-2}}) \qquad (2)$$

where α is a correction for unequal heating below the sensors, z is the measurement height, ρ (g m^{-3}) is air density, and C_p (J g^{-1} K^{-1}) is the specific heat of air at constant pressure (Paw U *et al.*, 1995; Snyder *et al.*, 1996; Spano *et al.*, 1997a). The ratio $a/(d+s)$ is the ratio of the mean ramp amplitude a to the sum of the ramp period d and the quiescent period s between successive ramps. Owing to unequal heating of air parcels below the temperature sensor height, H derived from surface renewal is calibrated against H from a sonic anemometer to determine the α factor (Equation (2)). However, this calibration factor is quite stable regardless of weather conditions, and only needs to be recalculated when there are major changes in the plant canopy (Paw U *et al.*, 1995). More details concerning the surface renewal method can be found in Snyder *et al.* (1996); Spano *et al.* (1997a,b, 2000), and Paw U *et al.* (2005).

Another technique, called the canopy cover coefficient (CCC) or crop coefficient method, has had limited application in wetlands, yet it has the potential for broad application in areas with monotypic or low-diversity vegetation. In this approach, ET from a vegetated surface is estimated as a function of the crop coefficient K_c, which is a factor derived for each plant surface, and $\mathrm{ET_o}$, which is the reference evapotranspiration or the measure of evaporative demand for a particular region (Allen *et al.*, 1994):

$$\mathrm{ET} = \mathrm{ET_o} \times K_\mathrm{c} \qquad (3)$$

The $\mathrm{ET_o}$ established by the American Society of Civil Engineers has become widely used and is based on a modified Penman–Monteith equation for a broad surface of short vegetation (similar to 0·12 m tall, cool-season grass) having surface resistance $r_\mathrm{s} = 0{\cdot}50$ s m^{-1} during daylight hours and $r_\mathrm{s} = 200$ s m^{-1} during the night (ASCE-EWRI, 2005). Robust ET estimates for a particular plant species or community are commonly computed as the product of a K_c value and the $\mathrm{ET_o}$ rate from a nearby weather station.

One of the biggest drawbacks of the CCC approach at this time is a major shortage of reliable K_c values for wetland plant species and plant community types within particular climate regimes. In addition, of the few K_c values that are available for wetlands, many are not comparable or even accurate due to the methodologies employed. For example, K_c values derived using lysimeter experiments have often resulted in unrealistic values (e.g. $K_\mathrm{c} > 2$), due to the strong influence of air advection (e.g. Towler *et al.*, 2004). Other K_c values have been derived using non-standardized $\mathrm{ET_o}$ values, thus precluding cross-comparisons between sites. Some K_c values were determined with inadequate fetch of vegetation. We have only found a handful of K_c values for wetlands that were determined using both appropriate methods and comparable methodologies (Table I).

The purpose of this study was to estimate ET and determine monthly K_c values during the growing season for a small, restored marsh in the Sacramento–San Joaquin Delta, California, USA. The delta is a former 1400 km^2 tidal marsh that was drained and reclaimed in the past 150 years and currently is a major agricultural area (Atwater *et al.*, 1979). It is the most inland part of the San Francisco Bay Estuary, and its climate is strongly influenced by the western winds (the Delta Breeze) that develop in the summer and early fall. The delta is situated in a semi-arid region where water use is a topic of major concern; yet, so far, little research has been done to determine the consumptive water requirements of the remaining wetlands in the region. The restored *Typha–Schoenoplectus acutus* marsh studied in this project is a prototype wetland, as much more wetland restoration is anticipated in the delta in the coming years (CALFED Bay-Delta Program, 2000). ET rates were measured from May to October for 3 years in order to (1) characterize monthly K_c values adequately and (2) investigate variability in K_c values due to the particular climate regime of the area.

STUDY SITE

The research was conducted on Twitchell Island (38°06′25″N, 121°38′49″W), a 1490 ha island located in the Sacramento–San Joaquin Delta, that was once part of the historic tidal marsh in the region (Figure 1a). The climate in the delta is characterized as Mediterranean with cool, wet winters and hot, dry summers (Atwater, 1980). Mean annual precipitation is approximately 36 cm, but

Table I. Crop coefficient values for wetland plants determined using standard methods

ET_o	ET measurement method	Species	K_c for site	Reference
P–M[a] for alfalfa or grass	Lysimeters (two 1 m × 1 m × 1·25 m depth lysimeters in 6 m × 6 m plots of same vegetation)	*Typha latifolia* (cattail)	Stage: initial period, 1 May (0·3); midseason period, 6 Jun–5 Sep (1·6); ending period, 1 Oct (0·3); Utah	Allen (1995)
Same as above	Same as above	*Scirpus lacustris* (bulrush)	Stage: initial period, 1 May (0·3); midseason period, 8 Jul–7 Aug (1·8); ending period, 1 Oct (0·3); Utah	Allen (1995)
Same as above	BREB[b]	*T.latifolia*	Stage: initial period, 1 May (0·3); midseason period, 15 Jun–15 Sep (1·15); ending period, 1 Oct (0·3); 9 ha marsh, Utah	Allen (1995)
Same as above	Lysimeters (3·5 m diameter × 0·9 m deep)	*T.domingensis*	Stage: initial period, 15 Mar (0·6); midseason period, 1 May–15 Sep (1·0); ending period, 15 Oct (0·6); 1545 ha marsh, southern Florida	Abtew and Obeysekera (1995)
P–M for grass	Lysimeters (3·6 m diameter × 1 m deep)	*Cladium jamaicense* (sawgrass)	May–Oct = 1·09, Nov–Apr = 0·73, annual = 0·98, 2700 ha marsh, Florida	Mao *et al.* (2002)
Same as above		*T.domingensis*	Jan = 0·51, Feb = 0·61, Mar = 0·64, Apr = 0·73, May = 0·87, Jun = 0·87, Jul = 0·78, Aug = 0·76, Sep = 0·86, Oct = 0·78, Nov = 0·65, Dec = 0·56; annual = 0·77, 2700 ha marsh, Florida	
P–M for grass	BREB	*Phragmites australis* (common reed)	0·53 (dry days between 24 May and 28 Aug 2001); 243 ha reed-bed, UK	Peacock and Hess (2004)

[a] P–M is the Penman–Monteith equation.
[b] BREB is the Bowen ratio energy balance method.

actual yearly precipitation varies from half to almost four times this amount. Over 80% of precipitation occurs from November to March. The majority of Twitchell Island (80%) is owned by the California Department of Water Resources, and the rest is owned privately. The boundaries of the island have been maintained by levees that were originally built in 1869 and have been fortified several times since (Thompson, 1957; Ingebritsen and Ikehara, 1999). Land use on the island has consisted of irrigated farming and pasture since the late 1800s. The current elevation of the land surface is between 3·0 and 5·5 m below sea level, due to ongoing land-surface subsidence in the region (California Department of Water Resources, 1995).

In 1997, the East Pond (2·65 ha; Figure 1b) and the West Pond (2·75 ha) were constructed adjacent to each other in the centre of Twitchell Island by excavating the remnant peat soils and using this material for the pond walls. Prior to flooding, hardstem bulrush (*S. acutus*) cuttings were planted in the ponds. In October 1997, the ponds were flooded in order to restore wetland function. Since that time, water has been delivered by pipe to both ponds from the San Joaquin River at a rate of approximately 960 l min^{-1}. Weirs along the north side of both ponds maintain a constant water depth of approximately 55 cm in the East Pond and 25 cm in the West Pond. Subsequent to flooding, the ponds were quickly colonized by three species of cattail (*Typha latifolia, T. domingensis*, and *T. angustifolia*). Analysis of HyMap™ Hyperspectral images (HyVista Corporation) taken in June 2003 revealed that emergent macrophytes covered approximately 40% of the East Pond and 80% of the West Pond. Within the ponds there are also several floating aquatic plants (*Ludwigia peploides* and *Lemna* sp.) and submerged aquatics (*Potomageton* sp. and *Myriophyllum* sp.), all of which are common in delta marshes (nomenclature follows Hickman (1993)). Full canopy height of vegetation in the ponds was reached by the end of June during each year of the study period.

METHODS

On 23 May 2002, an ET measurement station was assembled in the East Pond (Figure 1b). The fetch was 500 m in the predominant upwind direction (west), and less in the north–south direction, from which wind was infrequent. A footprint analysis conducted for the eddy covariance measurements (Schmid, 1994) revealed that most of the measured signal came from the East Pond with some coming from the West Pond. The source area was predominantly in *Typha* spp. and *S. acutus* stands, ranging from 0·75 m tall during the winter to 2–2·5 m

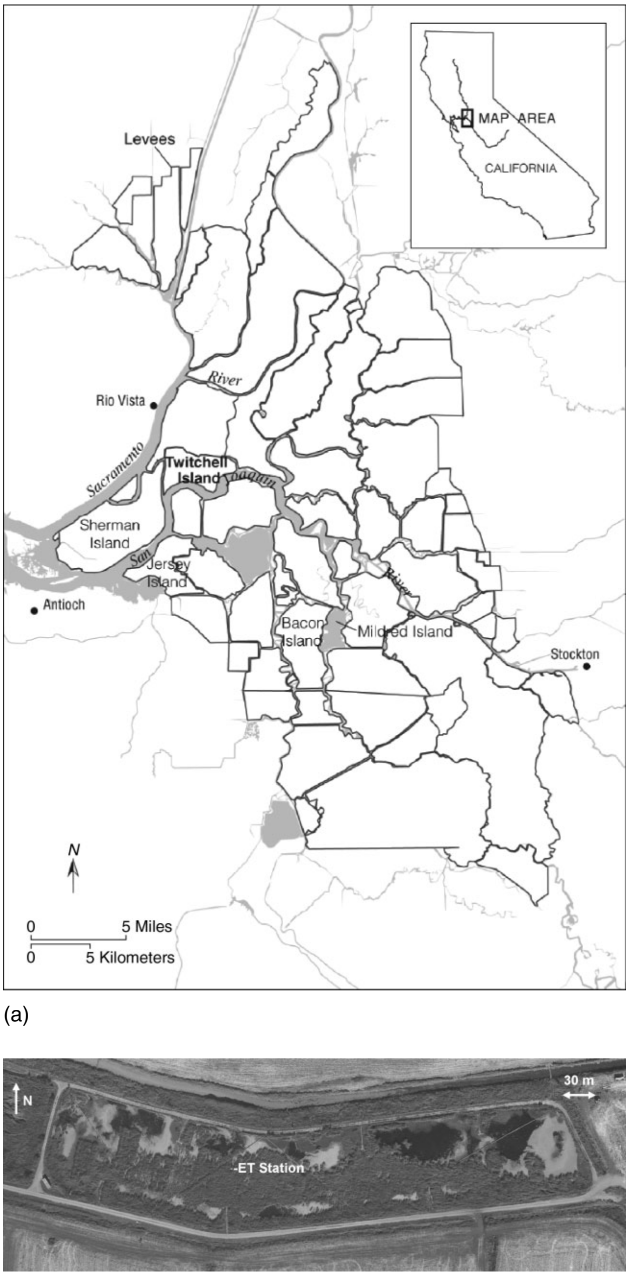

Figure 1. (a) Map of the Sacramento–San Joaquin Delta of California showing the location of Twitchell Island and (b) grey-scale aerial photograph of the East Pond, which is located in the centre of Twitchell Island

tall throughout the height of the summer growing season. For the purposes of this paper, the site where ET was measured will be referred to as the East Pond.

The ET station contained the following instruments: two data-loggers (CR23X and CR10X, Campbell Scientific, Inc. (CS), Logan, UT, USA), a sonic anemometer (CS CSAT3 3-D), two fine-wire (76·2 μm) thermocouples (FW003, CS), a net radiometer (Q7·1, Radiation and Energy Balance Systems (REBS), Bellevue, WA, USA), a temperature and relative humidity probe (CS HMP45C), three temperature probes (CS 108), a soil heat flux plate (HFT3, REBS), and an open-path infrared gas analyser (7500, Li-Cor, Inc., Lincoln, NE, USA). The sonic anemometer, thermocouples, net radiometer, temperature and relative humidity probe, and the gas analyzer were set up at 2·9 m above the water surface. This instrument height was chosen to maximize the greatest source area within the wetland and minimize the effects of the surrounding agricultural crops. Factors such as the shape, size, and height of the vegetation, as well as the orientation of the wetland to the prevalent wind direction, were taken into account when determining the instrument height. CS 108 temperature probes were placed (1) at the bottom of the pond, which comprises the boundary between the water and peat surface, (2) at approximately 25 mm below the top of the water surface, and (3) midway between the other two sensors. The temperature probes were shaded from direct sunlight with floating Styrofoam to minimize the direct absorption of short-wave radiation. In addition to measuring the temperature of the water, a soil heat flux plate was placed at a depth of 0·08 m below the peat soil surface. During the study, however, the sensor showed no energy flux at that depth in the peat soil. Throughout the growing season (spring through fall), weekly visits were made to download the data-loggers, check for instrument alignment and damage, and conduct general maintenance. The open-path infrared gas analyser was calibrated monthly.

The surface renewal method for determining sensible heat flux density requires measurement of high-frequency temperature data and the use of a structure function (Van Atta, 1977; Snyder *et al*., 1996) to determine the mean ramp characteristics during a sampling period. For the surface renewal measurements, the CS CR10X data-logger program was used to collect 4 Hz frequency temperature data from the two fine-wire thermocouples. The temperature differences between the current reading and two previous readings with the time lags $r = 0{\cdot}5$ s and $r = 1{\cdot}0$ s were computed. The two temperature differences for each of the two sensors were raised to the second, third, and fifth powers and the means were calculated over a 0·5 h sampling period to obtain the moments $S^2(r)$, $S^3(r)$, and $S^5(r)$, respectively. Following van Atta (1977), the mean ramp amplitude was determined by solving the following third-order equation for the mean ramp amplitude a:

$$a^3 + pa + q = 0 \tag{4}$$

where

$$p = 10S^2(r) - \frac{S^5(r)}{S^3(r)} \tag{5}$$

and

$$q = 10S^3(r) \tag{6}$$

The inverse ramp frequency was calculated from the amplitude a and third moment as

$$d + s = -\frac{a^3 r}{S^3(r)} \tag{7}$$

Then the uncalibrated sensible heat flux density H' was calculated using Equation (2), and the α calibration factor was determined as the slope of a regression through the origin of the sensible heat flux measured with the sonic anemometer (H_s) versus H'. Note that the eddy covariance system was only used to measure H_s, which was used to calibrate the surface renewal estimates. The α factors tend to be insensitive to wind speed, direction and other meteorological factors, but they do vary with the canopy density. As a result, the α factors change as the wetland canopy develops and senesces during the season. Because of minor maintenance downtime, it was not possible to calculate α factors continuously during all three seasons. Also, the α factors were similar but not exactly the same each season. Therefore, for the purpose of our determinations of H, the following procedure was followed. A relationship between α and time was developed using the monthly mean α factors for each year and the same general relationship was used for all three years. The monthly mean α factors were plotted versus date, and general relationship lines were subjectively drawn to match the means as closely as possible. The standard deviation of α was computed for each month using data from all three years and the mean of the standard deviations was plotted as error bars in Figure 2. When there were fewer than 3 years of α values for a month, the error bars were not plotted. The generalized curve matched the monthly means well during the study period.

Using the generalized α factor curve and H', the surface renewal sensible heat flux density $H = \alpha H'$ was computed each 0·5 h using Equation (2). LE was determined by calculating the residual of the energy balance equations using measured or estimated R_n and G and $\alpha H'$ as

$$\mathrm{LE} = R_n - G - \alpha H' \quad (\mathrm{W\ m^{-2}}) \tag{8}$$

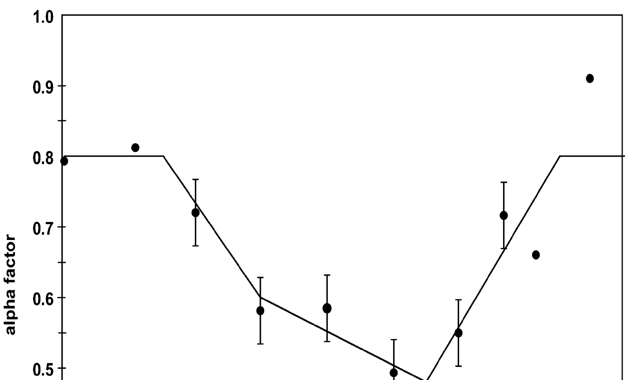

Figure 2. A plot of the generalized α factor curve and the mean monthly α factors for 15 April–31 December, 2002–2004. The error bars represent the mean of the standard deviations of α factors for months having 3 years of data. The points without error bars had fewer than 3 years of data

The surface renewal energy balance calculations were done on a half-hourly basis, and daily total energy fluxes of R_n, G, H, and LE were computed from the 0·5 h data.

Hourly meteorological data were collected by a CIMIS station (Snyder and Pruitt, 1992) over a large irrigated grass field approximately 1 km distant from the experimental site. The data were downloaded from the CIMIS website (http://wwwcimis.water.ca.gov/cimis). The hourly weather data were used to calculate reference evapotranspiration using the ASCE-EWRI (2005) modified Penman–Monteith equation for short canopies. The weather data included solar radiation R_s (which is converted to R_n using an algorithm in the ASCE-EWRI (2005) equation), air temperature T, dew-point temperature T_d, and wind speed and direction measured at 2 m height (U_2 and W_s respectively). Crop coefficient values were determined from daily wetland ET and $\mathrm{ET_o}$ data using Equation (3). The wetland ET was calculated by summing the 24 h of LE data and converting it to millimetres of water evaporated. A summary of the monthly weather observations for the three years is provided in Table II.

Rigorous quality assurance and control procedures were used to screen the data for determining (1) the α factor, (2) the hourly surface renewal-derived sensible heat flux, and (3) the daily and monthly K_c values. To determine the α factor, hourly values of uncalibrated, surface renewal-derived sensible heat fluxes were compared with hourly, sonic-derived sensible heat fluxes. When values from the surface renewal were unattainable due to low fluxes or unresolved statistical ramps, both the sonic and surface renewal values were eliminated from the α correction analysis. In addition, any sonic values from a wind direction that caused the instruments to interfere with the flow were also removed.

When H' data were available, LE was estimated using Equation (1), where $H = \alpha H'$ and α is the surface renewal calibration factor. When H' data were missing, LE was estimated as $\mathrm{LE} = b(R_n - G)$, where b was the slope of the linear regression through the origin of all available LE versus $(R_n - G)$ data in each year. Annually, there are 4416 possible hourly values during the period May–October, and the numbers of missing H' values were 304, 497, and 297 for 2002, 2003, and 2004, respectively. The corresponding b values were 0·68, 0·65, and 0·72. Most of the missing data were observed during the night, when both the H and LE fluxes were low.

The last correction involved post-field assessment. Any obvious net radiation outliers that exceeded solar radiation were deleted. Data collected during days when the Twitchell Island CIMIS station recorded precipitation were deleted because of errors associated with effects of precipitation on the measurement equipment. K_c values that were negative were deleted, as well as a few unrealistically high outliers that were out of the bounds of measurements for wetland plants and

Table II. Mean ET_o, rainfall (Pcp), solar radiation R_s, maximum air temperature T_x, minimum air temperature T_n, dew-point temperature T_d, and wind speed U_2. Temperature and humidity were measured at 1·5 m and wind speed at 2 m height over irrigated grass. ET_o was calculated using the hourly Penman–Monteith equation (ASCE-EWRI, 2005)

Month	ET_o (mm day^{-1})	Pcp (mm)	R_s (MJ m^{-2} day^{-1})	T_x (°C)	T_n (°C)	T_d (°C)	U_2 (m s^{-1})
2002							
Jan	1·0	14	7·9	11·3	1·4	2·8	2·1
Feb	2·0	29	12·6	16·8	3·2	5·5	2·2
Mar	3·3	44	17·5	18·1	4·8	4·6	3·3
Apr	4·5	3	22·0	20·2	8·2	7·4	4·3
May	6·3	19	27·1	24·0	10·5	7·5	4·3
Jun	7·9	0	30·7	28·1	13·8	9·4	4·8
Jul	7·5	0	28·5	30·6	14·8	10·9	4·6
Aug	6·5	0	26·2	29·6	13·7	10·5	4·3
Sep	5·4	0	21·0	29·7	13·1	8·8	3·5
Oct	3·5	0	15·3	24·1	8·6	6·3	3·1
Nov	1·5	48	8·7	18·3	4·8	6·1	2·2
Dec	0·9	152	5·7	13·4	4·1	5·9	3·3
2003							
Jan	0·6	22	5·4	12·8	5·8	7·6	1·8
Feb	2·1	32	12·0	15·7	3·4	4·4	2·6
Mar	3·4	48	17·5	19·2	7·0	7·1	3·5
Apr	3·6	46	19·3	17·4	6·4	6·3	3·6
May	6·0	16	26·1	24·1	10·6	8·7	4·0
Jun	7·4	0	27·9	27·6	13·7	10·2	5·1
Jul	8·1	0	27·1	32·4	16·7	10·4	4·5
Aug	6·3	5	24·2	29·8	15·2	11·9	4·3
Sep	5·4	0	20·4	29·5	14·0	10·3	4·2
Oct	3·8	2	14·9	26·7	9·8	7·4	3·2
Nov	1·4	42	8·8	15·9	3·6	5·3	2·1
Dec	0·7	88	5·0	12·7	4·6	5·8	2·8
2004							
Jan	0·7	49	5·3	11·2	4·0	4·9	2·2
Feb	1·6	107	8·8	14·9	4·6	5·4	2·9
Mar	3·6	14	16·8	22·0	7·8	7·9	3·5
Apr	5·4	2	21·3	22·7	8·8	6·1	4·4
May	6·3	2	25·9	24·5	11·5	8·6	4·7
Jun	8·0	0	29·0	27·6	14·3	9·5	5·8
Jul	7·4	0	28·4	29·2	14·9	11·8	4·7
Aug	5·9	0	24·6	29·9	15·3	11·9	2·8
Sep	5·5	16	20·6	29·5	12·6	8·7	3·5
Oct	3·1	63	13·8	22·4	9·6	8·1	3·1
Nov	1·4	42	8·5	15·5	4·5	5·4	2·1
Dec	0·8	93	5·6	11·8	2·3	4	2·6

crops (Drexler *et al.*, 2004). Generally, the unrealistically high outliers occurred during low ET or rainy periods. Table III shows the number of days of data that were used to calculate K_c values for the marsh each month.

RESULTS

Surface renewal ET for the East Pond during the May–October study period averaged 6·0 mm day^{-1} (SD = 1·9 mm day^{-1}) with a range of 0·8 to 12·2 mm day^{-1}. A plot of sensible heat flux density H for the sonic anemometer versus surface renewal showed a close relationship between the two parameters, with root-mean-square errors between 1·5 and 1·7 MJ m^{-2} day^{-1} for each year of the study (Figure 3).

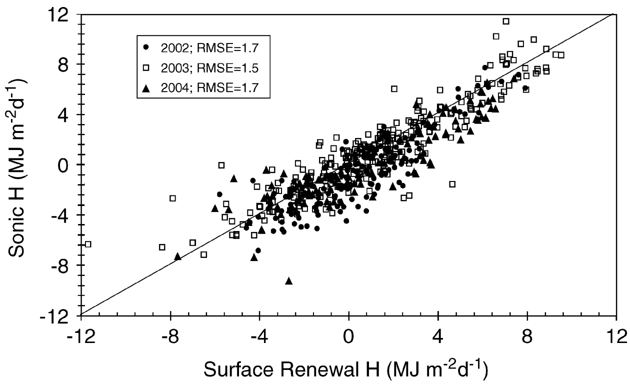

Figure 3. A plot of sensible heat flux density H for the sonic anemometer versus surface renewal and the root-mean-square error by year

During the calendar years 2002–2004, the monthly means of daily ET_o rates from the CIMIS station on Twitchell Island ranged from 0·7 to 7·9 mm (overall mean for the study period: 4·0 mm; SD = 2·3 mm). For the same period, the monthly means of daily ET rates from the East Pond measured using surface renewal ranged from 0·8 to 8·6 mm (overall mean: 3·8 mm;

Table III. Mean K_c values and standard deviations (in parentheses) from 2002–2004; n is the number of days of usable data per month; 'best estimate' is the overall mean for each month for the study period

	2002		2003		2004		Best K_c (SD) estimate
	K_c (SD)	n	K_c (SD)	n	K_c (SD)	n	
May	0·73 (0·11)	28	0·77 (0·14)	29	0·90 (0·11)	30	0·80 (0·14)
June	0·97 (0·08)	30	0·90 (0·18)	30	0·90 (0·09)	30	0·92 (0·13)
July	1·00 (0·07)	31	1·08 (0·06)	31	0·97 (0·14)	31	1·02 (0·10)
August	1·00 (0·08)	31	1·10 (0·07)	29	1·18 (0·24)	31	1·09 (0·17)
September	1·02 (0·08)	30	1·02 (0·16)	30	0·99 (0·12)	28	1·01 (0·12)
October	0·91 (0·09)	30	0·91 (0·23)	30	0·88 (0·16)	21	0·90 (0·17)
Best overall estimate							0·95

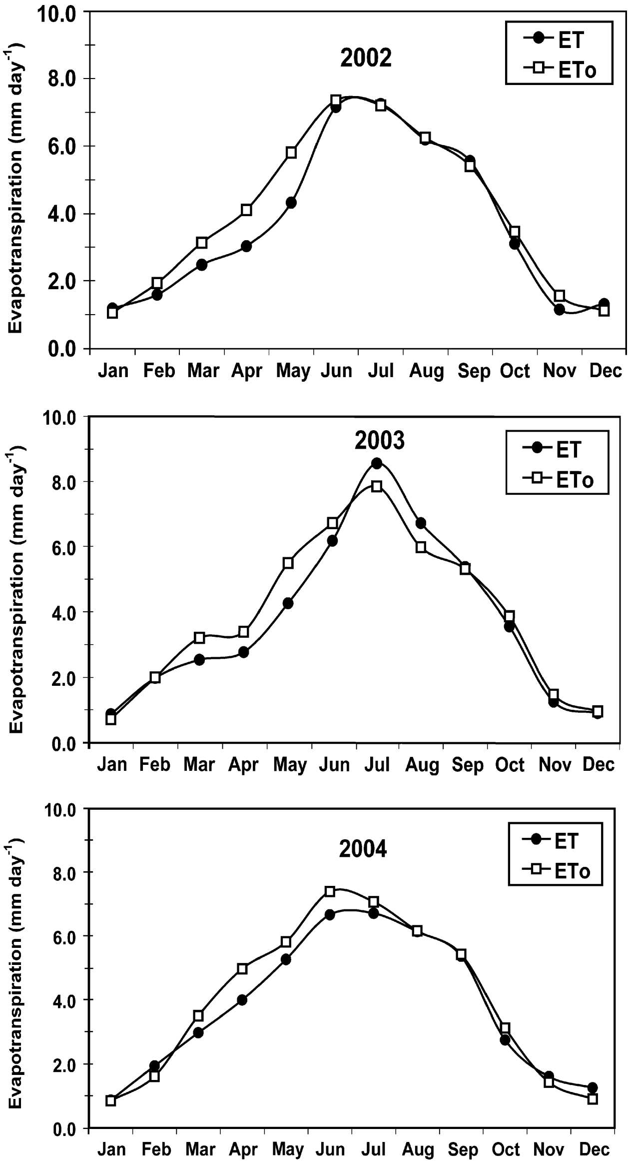

Figure 4. The relationship between monthly means of daily ET_o from the Twitchell Island CIMIS station and surface renewal ET from the East Pond for (a) 2002, (b) 2003, and (c) 2004

SD = 2·3 mm) (Figure 4). The differences between ET and ET_o were generally quite small. The greatest divergence between the parameters occurred during the spring months of each year, when ET_o was greater than ET (Figure 4). In 2003, there was also a divergence in July and August when ET was greater than ET_o (Figure 4).

The monthly means of daily crop coefficients during the study period ranged from 0·73 (May 2002) to 1·18 (August 2004) (Table III). The 'best' estimate of the monthly K_c values was determined as the average K_c for the same month over the three years. May had the lowest best estimate for K_c (0·80) and August had the highest best estimate for K_c (1·09). The overall K_c estimate for the entire study period was 0·95. The number of days of usable data per month throughout the study period ranged from 21 to 31, with a mean of 29·4 days.

There were periods after full canopy cover was achieved when daily K_c values varied considerably in the East Pond. Figure 5a shows an example of meteorological data during 24–26 July 2002 when daily K_c values were quite low (between 0·85 and 0·93) and then returned to the monthly mean of 1·0 by 27 July 2002. Figure 5b show meteorological data between 8 and 14 August 2004, when daily K_c values were quite high (between 1·3 and 1·8; monthly mean: 1·18). Close examination of these data reveal several major differences between these time periods. Although R_n was similar during both periods (daily peaks around 700 W m^{-2}), LE in the East Pond was greater on the whole during the August 2004 period than the July 2002 period. ET_o and LE were quite similar to each other during much of the July 2002 period, but on some days these factors differed by over 100 W m^{-2} at the peak of the day during the August 2004 period. The G term during the July 2002 period hovered between 250 and 300 W m^{-2} during the peak of the day, whereas it was mainly between 100 and 200 W m^{-2} during the August 2004 period. The daily peak in temperature during the July 2002 period was just around 30 °C except for 29 July, when it was 26 °C. In the August 2004 period, the daily peak in temperature was hotter, reaching up to about 35 °C on some days. In the July 2002 period, wind speeds hovered at about 5 m s^{-1}, whereas in the August 2004 period the wind speeds were at or near zero for most of the time. The H term generally reached higher daily peaks during the July 2002 period than during the August 2004 period. In addition, the H term was much

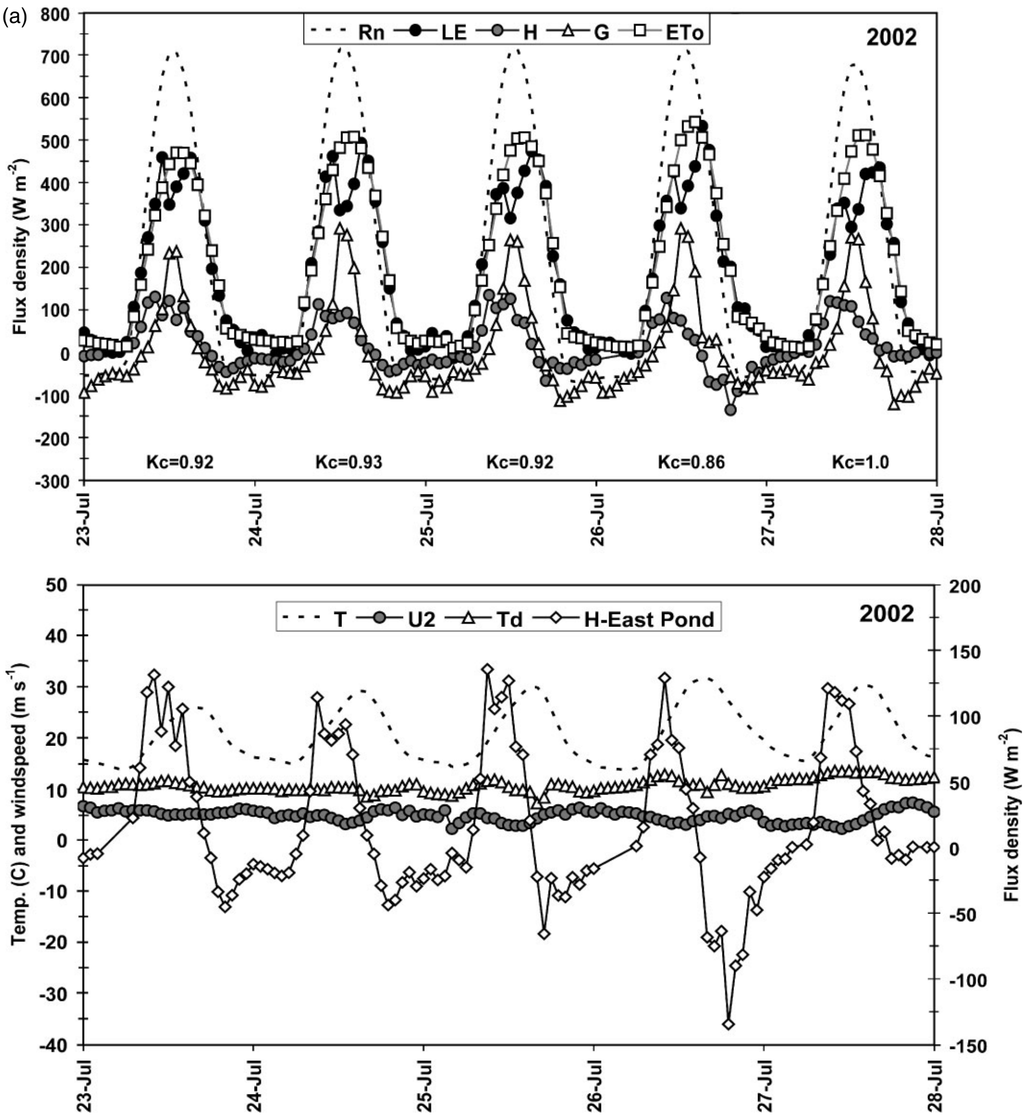

Figure 5. Major energy budget components and climate variables for the East Pond when there was a full canopy and K_c values were (a) low (24–26 July 2002) and (b) high (8–13 August 2004) relative to mean values (see Table III for explanation of terms)

more negative at night during the August 2004 period than during the July 2002 period (Figure 5).

DISCUSSION

The surface renewal technique, used with a changing α factor during the growing season (Figure 2), provided good estimates of ET that were highly comparable to those derived from the eddy covariance approach (Figure 3). The technical ease of application and low cost make the surface renewal technique highly promising. Because surface renewal has lower fetch requirements than eddy covariance (K.T. Paw U, University of California, Davis, CA, personal communication), it may be particularly well suited to wetlands with limited fetch and patchy vegetation for which ET estimates are sparse (Drexler *et al.*, 2004).

The mean ET during the growing season at the East Pond was 6 mm day^{-1}, which is greater than most of the ET rates for emergent wetlands shown in Table IV. The only examples of greater ET rates are for a marsh in arid central Spain (Sanchez-Carrillo *et al.*, 2004) and cattails grown in lysimeters in Utah, USA (Allen *et al.*, 1992), sites in which advection was reported to have occurred. The relatively high ET rates at the East Pond can be attributed to high wind speeds and the semi-arid, Mediterranean climate of the region, where summer air temperatures reach 35 °C and higher, and the permanently flooded condition of the wetland, which results in very low surface resistance of the vegetation.

The relationship between ET in the East Pond and ET_o from the CIMIS station on Twitchell Island changed through the course of the growing season (Figure 4). This indicates changes in the way R_n was distributed to components of the energy budget in the wetland versus the CIMIS station. Initially, in the spring, some of the available energy in the wetland was used to heat up the standing water (Figure 6), which is known to be an

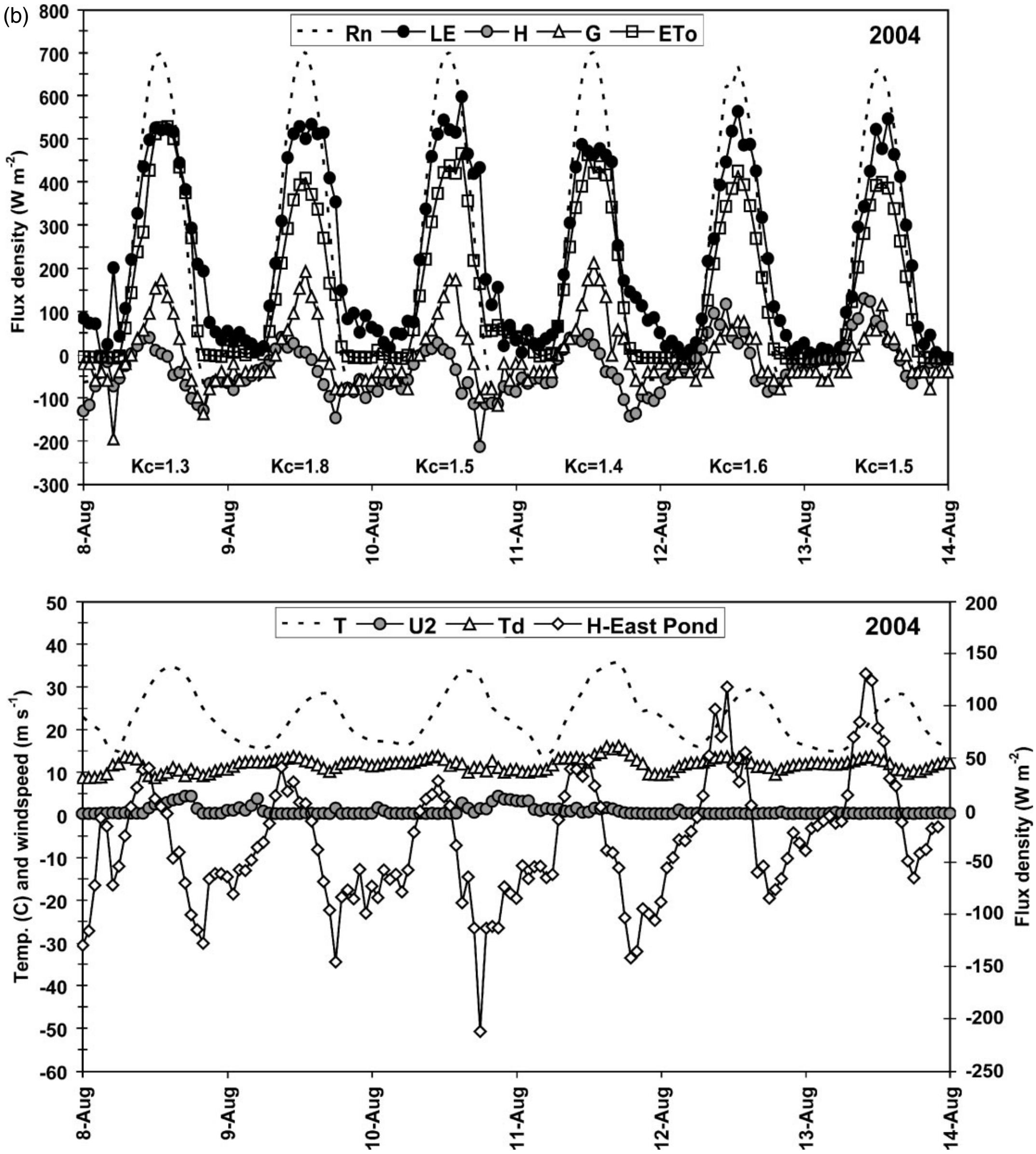

Figure 5. (*Continued*)

Table IV. A comparison of ET rates for a variety of wetland types with large emergent vegetation[a]

Wetland type	Location	Time of year	ET (mm day^{-1})	Reference
Reedbed	Kent, UK	24 May–28 Aug	∼0·5–5·0	Peacock and Hess (2004)
Scirpus acutus community	Nebraska, USA	Jun–Oct	3·5–6·5	Burba *et al*. (1999)
Mixture of emergent marsh, scrub-shrub, and open water	Indiana, USA	Jun–Oct	Mean: 3·6	Souch *et al*. (1998)
Arid floodplain wetland dominated by *Phragmites* and *Cladium mariscus*	Central Spain	1993–1998	Mean: 8·0	Sanchez-Carrillo *et al*. (2004)
Typha domingensis in lysimeters	Florida, USA	May, Jun, Jul, Aug, Sep, Oct	Monthly means: 5·4, 5·8, 5·2, 4·9, 3·2, 2·7	Abtew and Obeysekera (1995)
T. latifolia in lysimeters	Utah, USA	26 May–5 Oct	∼7·5–13·5	Allen *et al*. (1992)
Typha–Schoenoplectus marsh	Central Valley, California, USA	May–Oct	0·8–12·2	This study

[a] The '∼' symbol signifies that values were estimated from figures in the literature.

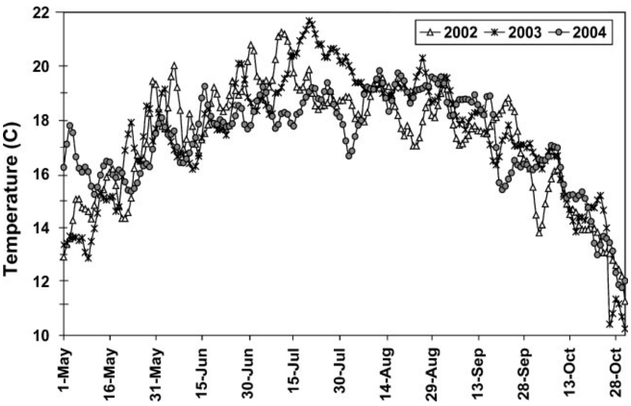

Figure 6. The temperature of standing water in the East Pond during the study period

important heat sink in wetlands (Souch *et al*., 1998). In contrast, in the grass canopy of the CIMIS station, more energy was available for the LE term during the spring (Figure 4). Once the standing water heated up in the wetland (by July; Figure 6), more of the energy from R_n was used for LE, and thus ET for the wetland and ET_o for the CIMIS station were similar. In 2003, however, which was the hottest year of the study, ET became greater than ET_o during the summer, probably because the taller canopy structure of the wetland resulted in a greater contribution of sensible heat flux to LE.

The crop coefficients for the East Pond are within the range of K_c values found in other wetland studies with similar vegetation in which standard methodologies were used (Tables I and III). During the summer months, the K_c values for the East Pond were less than the K_c values for *T. latifolia* and *Scirpus lacustris* in Utah (Allen, 1995). This is not surprising, as the summer climate in Utah is drier and hotter, on the whole, than that of the delta, leading to greater ET and K_c values. For the period May–October, K_c values for the East Pond were similar to K_c values for *T. domingensis* measured in lysimeters in the Everglades in Florida, USA (Abtew and Obeysekera, 1995), but greater than K_c values measured in a similar fashion in the Upper St Johns River basin of Florida, USA (Mao *et al*., 2002). The reason for this discrepancy between the two Florida sites is unclear; however, it may be an artefact of the location of lysimeters or the size and density of the *T. domingensis* growing in the lysimeters. Nevertheless, it is clear that climate has a major influence on K_c values of emergent wetland vegetation, the case in point being the great difference between crop coefficients for a reedswamp in the UK ($K_c = 0{\cdot}53$ for late May–August) and the East Pond ($K_c = 1{\cdot}01$ for June–August) (Tables I and III).

Variation in K_c values occurred both within months and between years (Table III). High within-month variation in K_c values was found for August 2004 and October 2003. Although numerous factors may be the cause of such variability, our analysis revealed that changing wind patterns were of particular importance. Changing wind patterns were related to the presence or absence of the Delta Breeze, a steady western wind that carries moist, cool air from the California coast to the delta. The Delta Breeze, which occurs during summer and fall afternoons, occasionally falters, resulting in little wind or a hot northern wind. These conditions lead to major changes in several energy components and result in high ET rates and, therefore, high K_c values (1·3–1·8), similar to those found by Allen (1995) in Utah (see results and Figure 5b). Conversely, when the Delta Breeze blows strongly, ET rates are lower and, therefore, K_c values are lower as well (0·86–0·93, Figure 5a).

High yearly variations in K_c values were found between May 2002/2003 and May 2004, between July 2002/2004 and July 2003, and between all three years in August (Table III). Such differences between years were found to be related to the temperature of standing water, air temperature, and/or wind speed (Table II, Figure 6). In May 2004, the air temperature, the temperature of the standing water, and the wind speed were higher than in May of 2002 and 2003, resulting in higher turbulence and more available energy for ET. In July 2003, the air and water temperature were much higher than in July of 2002 and 2004, resulting in the jump in ET and K_c values. During the month of August, water temperature does not appear to have been the significant factor causing the variation, because by this time the water had already reached its peak temperature (Figure 6). Instead, it seems that variations in air temperatures (August 2002 < August 2003 < August 2004; Table II) combined with the reduced frequency of Delta Breeze events with wind speeds over 4 m s^{-1} (five such events occurred in August 2002, one such event in August 2003, and no such events in August 2004) caused the consecutive increases in K_c values between years.

Crop coefficients have long been known to vary due to cloudiness, solar radiation, wind speed, temperature, and advection (Smith *et al*., 1991). In this study, wind *direction* and water temperature have been shown to have a strong influence over K_c values in a wetland. For this reason, K_c values derived from this study, especially in the summer and fall, would best be used for other wetlands in the delta or in a similar Mediterranean climate. Catering the K_c values to local climate conditions and the particular characteristics of a wetland is key to achieving good estimates (Allen, 1995). Successful application of the crop coefficient method to wetlands clearly requires that K_c values be derived *using standard methodology* for a wider variety of wetland surfaces under varying climate conditions.

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