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Quantifying the effects of advection on canopy energy budgets and water use efficiency in an irrigated wheat field in the North China Plain

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ABSTRACT

Competing demands for water with increasing population calls for developing strategies for increasing the crop water use efficiency (WUE) of irrigated crops, especially in the semiarid regions of the world. In this context, it is important to quantify the various factors that control the WUE of irrigated crops in these regions. Advection is an important factor that can have significant effects on the energy exchange in irrigated fields of arid regions, and hence control the crop canopy WUE (CWUE). An eddy covariance system was applied to measure water and heat fluxes and then to quantify advection in an irrigated winter wheat filed at the Yucheng Integrated Experiment Station, Chinese Academy of Sciences in the North China Plain (NCP) (36°57′N, 116°36′E, 28 m a.s.l.) in 2004. Priestley–Taylor parameter and canopy–air temperature differences were employed to identify the occurrence of advection. Effects of advection on canopy energy budgets and CWUE were examined by computing the equilibrium and advective evapotranspiration. It was found that enhanced advection occurs when the crop canopy–air temperature differences are negative or when the Priestley–Taylor parameter takes on values >1.5. Due to enhanced advection, the percentage of latent and sensible heat flux exchange contribution to the total water loss from the fields through evapotranspiration can exceed 50%, and CWUE decreased remarkably. Advection in the experiments probably resulted from drier soil regimes in the upwind areas.

1. Introduction

In applied micrometeorology, advection is usually defined as the horizontal divergence of sensible heat flux when it is large enough to produce a downward sensible heat flux close to the ground (McNaughton and Jarvis, 1983; Diaz-Espejo et al., 2005). Advection is expected to play a significant role in the energy exchange over large inhomogeneous surfaces. Inhomogeneity can be caused by differences in soil water regimes or by differing weather conditions. Some local advection also can occur due to different timings and amounts of irrigation across large farm fields. The North China Plain (NCP) accounts for about 60–70% of the winter wheat production in China. It has a temperate monsoon climate that is characterized by frequent winds and low precipitation (average about 115 mm) during the wheat growing season (from October to May) (Sun et al., 2006). Irrigation is widely practiced to supplement the scanty precipitation received and to reduce yield variability in these areas. Farmers practice irrigation on their individual farms in amounts and schedules that vary considerably across the NCP.

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Under those circumstances, local or regional heat energy advection can take place (Lee et al., 2004). Energy balance of the cropped fields can be distorted greatly under the influence of such advections. Evapotranspiration can also be greatly enhanced by advection in irrigated crop fields in the semi-arid and arid regions (Rosenberg, 1969; Hanks et al., 1971; Lang et al., 1974; Brakke et al., 1978). Windbreaks are sometimes used in the semiarid regions to suppress evapotranspiration (Brown and Rosenberg, 1972; Skidmore et al., 1972; McNaughton, 1988).

Lee et al. (2004) demonstrated the inequalities of eddy diffusivities for sensible heat and water vapor under the influence of regional or local advection. Using mini-lysimeters in small plot experiments, Diaz-Espejo et al. (2005) illustrated the significant effects of micro-scale advection on the partitioning of available energy. Studies focused on examining the effects of heat energy advection on CWUE and energy budgets in irrigated fields is lacking. Therefore, the objectives of this study were (1) to identify the requirements for the occurrence and enhancement of latent and sensible heat energy advection, and (2) to quantify the effects of advection on canopy energy budgets and CWUE in irrigated wheat fields in the NCP.

2. Theory

2.1. *Equilibrium and advective evapotranspiration*

Considering the effects of advection on evapotranspiration, McNaughton (1976) introduced the concepts of advective enhancement and advective depression of evaportranspiration rates. Evapotranspiration from crop fields (E) can be expressed as the sum of an equilibrium term (E_{eq}) contributed by the available energy at the site, and an advective term (E_{ad}) due to the extra energy made available at the site through advection. Hence

$$E = E_{eq} + E_{ad} \tag{1}$$

where E_{ad} is positive for advective enhancement or negative for advective depression. Equilibrium evaporation can be computed as (McNaughton, 1976; Raupach, 1991; Pereira, 2004)

$$E_{eq} = \frac{\Delta}{\Delta + \gamma}(R_n - G) \tag{2}$$

where Δ is the slope of the temperature–saturation vapor pressure relationship, γ the psychometric constant, R_n the net radiation above the canopy, and G the soil heat flux at the ground surface. If local or regional advection occurs, actual evapotranspiration deviates from the equilibrium point, and shows enhancement or depression. This effect does not depend on net radiation but on exchanges of latent and sensible heat energy fluxes at the canopy–air interface (McNaughton, 1976). When E is greater then E_{eq} due to warm and dry air entering the canopy, the sensible heat is converted to latent heat and canopy evapotranspiration is enhanced without consuming additional available energy.

Eq. (1) can be rewritten in the following form:

$$E_{ad} = E - E_{eq} \tag{3}$$

Eq. (3) is usually used to describe the energy exchange between sensible and latent heat at the canopy surface (McNaughton and Jarvis, 1983; Smith et al., 1997). E_{ad} is positive when E is depressed by advection and negative when enhanced. The ratio

$$R_{ad} = -\frac{E_{ad}}{E} \tag{4}$$

is usually used to describe the percentage contribution of advection to E (Smith et al., 1997).

2.2. *Priestley–Taylor parameter*

Priestley and Taylor (1972) proposed that E can be computed by

$$E = \alpha E_{eq} \tag{5}$$

where α is called the Priestley–Taylor parameter. The Priestley–Taylor approach is based on the assumption that the effect of turbulence is small compared to the effect of radiation, so the aerodynamic and canopy resistances are considered as zero. This estimation of E depends on the accurate determination of the value of α, which is a function of the Bowen's ratio and temperature and expressed as

$$\alpha = \frac{\Delta + \gamma}{\Delta(1 + \beta)} \tag{6}$$

where β is the Bowen's ratio, which is the ratio of sensible heat flux (H) to latent heat flux (LE), and can be estimated from measurements of gradients of temperature and vapor pressure above an evaporating surface, i.e:

$$\beta = \frac{H}{\mathrm{LE}} = \gamma \frac{K_h}{K_w} \frac{\delta T}{\delta e} \tag{7}$$

where δT and δe are the vertical temperature and vapor pressure differences above the canopy, respectively. K_h and K_w are the eddy diffusivities for sensible heat and water vapor, respectively. In general, K_h can be taken equal to K_w in the absence of advection.

The Priestley–Taylor parameter has a standard value of 1.26 for wet surfaces (Priestley and Taylor, 1972; Stannard, 1993). However, in practice, α varied widely with different vegetation types, soil moisture conditions and strength of advection (Nichols et al., 2004). Flint and Childs (1991) reported α values ranging from 0.7 to 1.6. Jury and Tanner (1975) reported values as large as 1.57 under strongly advective conditions. Pereira and Nova (1992) showed that the value of 1.26 is suitable for potential conditions, but invalid under advective conditions. Lee et al. (2004) showed that the equality of K_h and K_w is not attained in advective conditions. Hence, Bowen's ratio Eq. (7) cannot be used to calculate the value of α. Pereira (2004) proposed an alternative method to determine the Priestley–Taylor parameter.

In Pereira's method, a parameter C (equal to a) was computed

$$C = \frac{1 + (\gamma/(\Delta + \gamma))(r^*/r_a)}{1 + (\gamma/(\Delta + \gamma)(r_e/r_a))} \tag{8}$$

where r^* takes the critical value of the isothermal resistance defined by Monteith (1965) as

$$r^* = \frac{(\Delta + \gamma)\rho C_p V_{pd}}{\Delta\gamma(R_n - G)} \tag{9}$$

where C_p is the specific heat of air, and V_{pd} the vapor pressure deficit. This method avoids using the equality assumption for K_h and K_w through introducing aerodynamic and canopy resistance.

This Priestley–Taylor approach requires calculation of the canopy resistance, which is generally scaled up from leaf stomatal resistance (the reciprocal of leaf stomatal conductance). Research on the prediction of leaf stomatal conductance is well established, from the original empirical model (Jarvis, 1976) to the coupled model combining photosynthesis and transpiration (Leuning, 1995). Yu et al. (2004) proposed a practical and simple model that is similar to a Jarvis-type model but is able to calculate the conductance directly from environmental variables whilst maintaining a relevant physiological basis. Under non-stressed soil water conditions, the stomatal conductance (g_s) at leaf level can be computed by (Yu et al., 2004)

$$g_s = m\frac{A_m\alpha_{int}I\eta}{A_m\alpha_{int}I + A_m\eta C_a + \alpha_{int}I\eta C_a}\frac{1}{1 + V_{pd}/V_{pd0}} \tag{10}$$

where A_m is the maximum catalytic capacity of Rubisco per unit leaf area, m a parameter, α_{int} the initial photochemical efficiency, η the initial slope of the CO_2 response curve, I the photosynthetically active radiation, C_a the CO_2 concentration of the air, and V_{pd0} a parameter reflecting characteristics of the response of stomata to atmospheric V_{pd}. The value of A_m is a function of temperature given by Collatz et al. (1991)

$$A_m = A_0\frac{Q_{10}^{(T_a - 25)/10}}{1 + \exp(-a_1 + b_1(T_a + 273)/(R(T_a + 273)))} \tag{11}$$

where A_0 is the maximum photosynthetic rate under ideal conditions, Q_{10} the temperature coefficient reflecting the sensitivity of photosynthesis to temperature, T_a the air temperature, R the universal gas constant, and a_1 and b_1 are fitting parameters.Canopy resistance can be scaled up from leaf resistance and leaf area index (L_{ai}), i.e.

$$r_c = \frac{1}{g_s L_{ai}} \tag{12}$$

Finally, aerodynamic resistance was calculated by (Thom and Oliver, 1977)

$$r_a = \frac{4.72(\ln(z - d)/z_0)^2}{1 + 0.54u} \tag{13}$$

where z is the reference height, d the displacement height, z_0 the roughness length, and u the wind speed. The terms z_0 and d can be represented as functions of the crop height (h). In the current study, $d = 0.56\,h$ and $z_0 = 0.13\,h$ were assumed based on Legg and Long (1975).

2.3. CWUE

Water use efficiency (WUE) has different definitions depending on the time and space scales of the processes and system aggregation it refers to (Steduto, 1996). Generally it is defined at the leaf, canopy or population levels. In this study, WUE is defined at canopy level (CWUE) as the ratio of CO_2 flux (F_c) to H_2O flux (E) over the canopy. Here, we assume a close canopy; and the CO_2 and H_2O flux released by the soil are very small and not included. It can be considered as the ratio of canopy carbon gains over water losses. Therefore, CWUE can be expressed as

$$\mathrm{CWUE} = \frac{F_c}{E} \tag{14}$$

3. Experiments

Experiments were conducted at the Yucheng Integrated Experiment Station (36°57′N, 116°36′E, 28 m a.s.l.), Chinese Academy of Sciences in the NCP located at about 350 km south of Beijing in 2004. Measurements were made at the center of a 300 m × 300 m field of winter wheat. Lands around the experimental field in a radius of about 5000 m were managed by local farmers and are characterized by different irrigation schedules and amounts. Fluxes of CO_2, latent and sensible heat were measured with an eddy covariance system installed at 2.1 m above the ground level. The system consisted of a fast response infrared gas analyzer (LI7500, LI-COR Inc.) and a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc.). Data were recorded with a data-logger (CR23X CSI) and the sampling frequency was 20 Hz for each channel. We calculated the half-hourly average values and used for the analysis. A radiometer (CNR1, Kipp & Zonen) was installed at 2.1 m above the ground to measure downward and reflected components of shortwave and long-wave radiation. Air temperature and relative humidity were measured with temperature/humidity probes (HMP45C, VAISALA). Wind speed and direction were measured. Two soil heat flux plates (HFP01SC, Hukseflux) was set at 0.10 m soil depth at the row and aisle position. The crop canopy temperature in the experimental field was measured with an infrared thermometer (IRT) installed on a bracket of the eddy correlation system with a 45° angle from the horizontal, detecting radiation in the 8–14 μm wave bands (Minolta/Land Cyclops Compac 3). Calibration of the IRT was performed prior to the measuring period using commercial black body surface. Canopy temperature was measured every minute and the half-hourly average values were recorded. Crop height and leaf area index (destructive sampling) were measured. Eddy covariance data were corrected by the WPL (Webb-Pearman-Leuning) method. Data from 15 to 24 April with 10 consecutive rain-free days were used in the analysis.

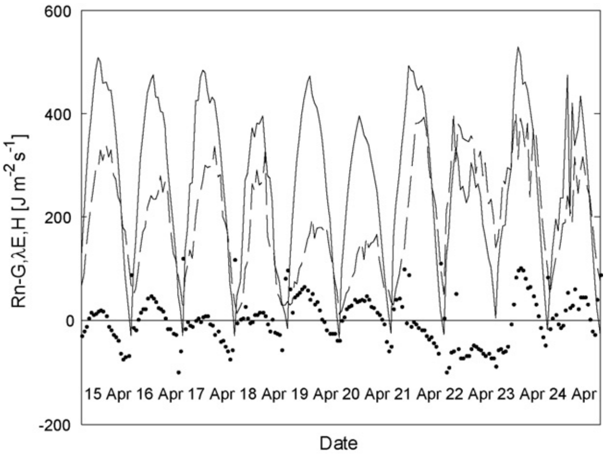

Fig. 1 – Available energy ($R_n - G$, solid line), latent heat flux (λE, dashed line) and sensible heat flux (H, circle line) over the period from 15 to 24 April 2004.

4. Results

4.1. *Energy balance*

In the eddy covariance studies $\lambda E + H$ were reported in the range of 60–90% of available energy ($R_n - G$) for forest in America (Constantin et al., 1998; Kelliher et al., 1997; Wilson et al., 2002). The average ratio of $\lambda E + H$ to $R_n - G$ is about 81% over the crop fields in NCP (Li et al., 2005). Fig. 1 showed the variations of $R_n - G$, λE and H balance in the experimental field during the 10 days period from 15 to 24 April 2004. We observed that on average the $\lambda E + H$ was 71% of $R_n - G$. Wilson et al. (2002) gave five reasons for the energy imbalance including: (1) sample errors associated with the eddy covariance and the independent available energy measurements, (2) a systematic bias in calibration or instruments, (3) neglected energy sinks, (4) the loss of low and/or high frequency contributions to the turbulent flux in the eddy covariance measurements, and (5) any other neglected advective losses of energy from the experimental field. We hypothesize that advection can be one of the important reasons of this energy imbalance. Evapotranspiration is one of the processes strongly influenced by the advection of thermal energy.

Table 1 – Soil water, and wind speed and direction data recorded at the experimental site from 12 to 25 April, 2004

Date	Soil water content (cm^3/cm^3)	Wind speed (m/s)	Wind direction (°)
12 April	0.26	1.26	217
13 April	0.42	2.80	195
14 April	0.38	2.23	200
15 April	0.37	4.48	204
16 April	0.35	2.88	205
17 April	0.34	3.56	195
18 April	0.32	0.91	164
19 April	0.32	2.76	196
20 April	0.31	0.68	164
21 April	0.31	2.66	212
22 April	0.30	4.17	74
23 April	0.28	3.19	91
24 April	0.27	2.13	170
25 April	0.26	1.74	158

4.2. *Observed advection in the experiment*

As shown in Fig. 1, advection occurs when the sensible heat flux is negative at or near the ground level (McNaughton and Jarvis, 1983). We observed enhanced advection, especially in the early morning and late afternoon during the 10 days (Fig. 1). Moreover, on 22 April, the sensible heat flux was continuously negative from 8 am to 6.00 pm (Fig. 1). Table 1 shows the soil water, and observed wind speed and direction during the 10 days period. Before the experiment on 13 April, soil moisture increased greatly due to high amount of irrigation applied in the field. Wind blowing over the experimental site on 22 and 23 April were from North to Northeast direction (Table 1) that probably brought dry air from unirrigated upwind areas. Enhanced advection observed on the 22 April was a consequence of the dry wind effect (Zermeno-Gonzalez and Hipps, 1997). Fig. 2 shows the relationship between the sensible heat flux and the Priestley–Taylor parameter values computed using Eq. (8). On average, sensible heat fluxes were positive when a-values were less than 1.5. For a values >1.5, enhanced advection occurred in the irrigated wheat field.

The canopy–air temperature difference, which reflects the direction of the sensible heat flux, also can be used to indicate the occurrence of advection. The signs of canopy–air temperature difference and sensible heat flux were the same throughout the experimental period. Fig. 3 shows the relation between canopy–air temperature difference and the

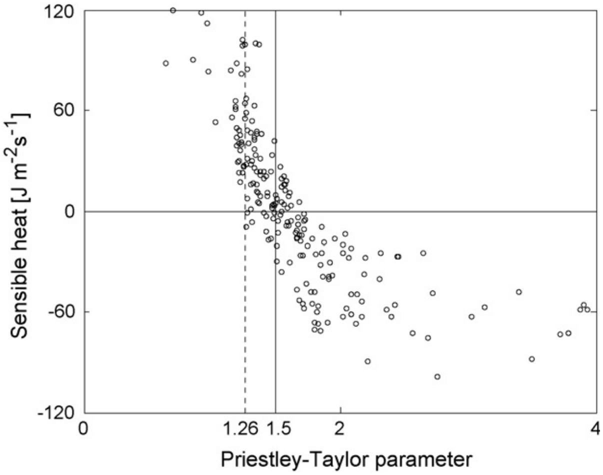

Fig. 2 – Relationship between the sensible heat flux and the Priestley–Taylor parameter. Each plotted point represents average half-hourly values (daytime) from 15 to 24 April 2004. The two vertical lines are for $a = 1.26$ (the standard value) (dashed), and $a = 1.5$ (solid). (a is the Priestley–Taylor parameter.) Plotted points falling on the right side of $a = 1.5$ line indicate the occurrence of advection (i.e., $H < 0$).

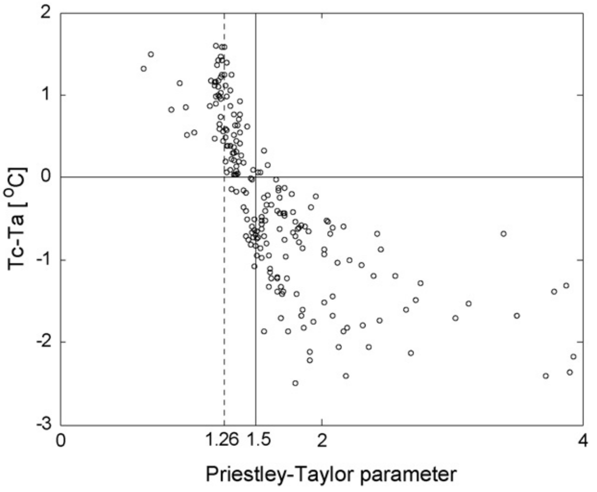

Fig. 3 – Relationship between the canopy–air temperature difference and the Priestley–Taylor parameter. Each plotted point represents a average half-hourly values (daytime) from 15 to 24 April 2004. The two vertical lines are for a = 1.26 (the standard value) (dashed), and a = 1.5 (solid). (a is the Priestley–Taylor parameter). Plotted points falling on the right side of a = 1.5 line indicate the occurrence of advection (i.e., $T_c - T_a < 0$).

Priestley–Taylor parameter. On average a negative value of canopy–air temperature difference existed when the Priestley–Taylor values were >1.5. Conversely, canopy–air temperature differences were positive for a-values smaller than approximately 1.5. These results indicate that both sensible heat flux and canopy–air temperature difference can identify advection, and a-values >1.5 is an indicator of enhanced advection. In small plot experiments, an a-value of 1.4 was taken as the threshold condition for occurrence of enhanced advection (Diaz-Espejo et al., 2005). The slightly larger value for a found in the current research perhaps resulted from the difference in experimental conditions between the two locations.

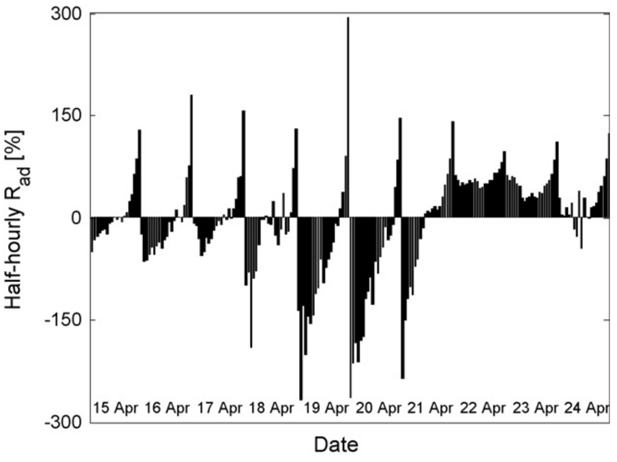

Fig. 4 – Computed half-hourly R_{ad} (the ratio of E_{ad} to E; where E_{ad} is the advective evapotranspiration, and E the total evapotranspiration) during the period from 15 to 24 April 2004.

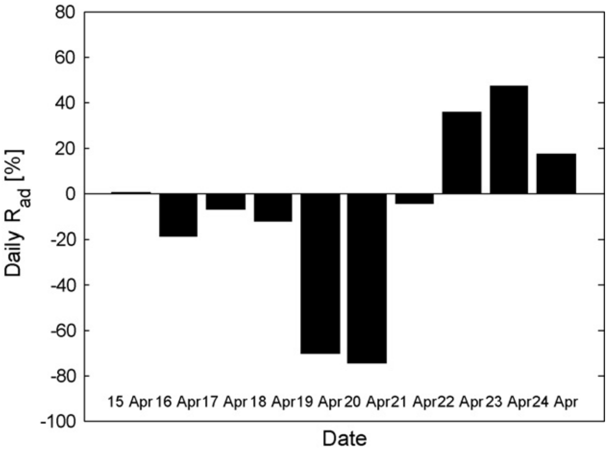

Fig. 5 – Computed daily R_{ad} (the ratio of E_{ad} to E; where E_{ad} is the advective evapotranspiration, and E the total evapotranspiration) during the period from 15 to 24 April 2004.

4.3. *Effects of advection on latent heat flux*

Fig. 4 shows R_{ad} (ratio of E_{ad} to E) during the experimental period. It shows that the R_{ad} represented by the advected energy flux is substantial. In a single day, sometimes the ratio can be positive or negative. This indicates that advection can either enhance or depress E. At some instances, the E_{ad} can reach as high as 300% of the total evapotranspiration under the conditions of enhanced advection. Fig. 5 shows the average daily (averaged by 8:00 am to 6:00 pm) R_{ad} for the 10 days. It was found that in the consecutive 10 days, 3 days showed obviously negative R_{ad} values, indicating E falling below the E_{eq}. Another 3 days showed remarkably positive R_{ad}, indicating E greater than the E_{eq} (enhanced advection). Remaining 4 days the E and E_{eq} were comparable in magnitude. For the days when enhanced advection occurred, R_{ad} could be more than 50%, which clearly shows that the effects of enhanced advection on canopy evapotranspiration should not be ignored.

4.4. *Effects of advection on CWUE*

It was found that CWUE dramatically decreased with increase in E_{ad} (Fig. 6). Affected by enhanced advection, some warm and dry air from the surrounding area enter the canopy, and some conversion (energy) from sensible heat flux to latent heat flux are affected through the extra water transpired (McNaughton, 1976). During the process of this energy exchange, canopy photosynthesis does not get affected as no additional solar energy entered the system. Therefore, CWUE decreased with the increase in the advective evapotranspiration. The four negative CWUE values observed were mainly due to either downward H_2O flux due to dew deposition or upward CO_2 flux due to soil respiration in some occasional cases (Fig. 6). In the CWUE calculations we considered the affects of the above two

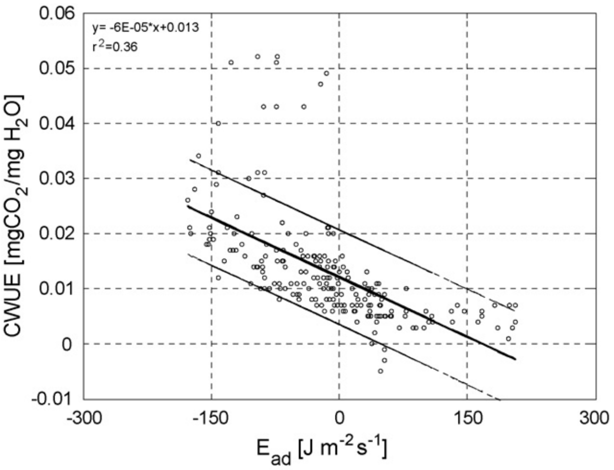

Fig. 6 – Relationship between canopy water use efficiency (CWUE) and the advective evapotranspiration (E_{ad}). The solid line indicates the regression equation and the dotted lines on each side of it represent the 95% confidence limits.

processes, resulting in negative CWUE values. Although the correlation coefficient between CWUE and E_{ad} was low ($r^2 = 0.36$), majority of the observations were within 95% confidence limits of the regression equation (Fig. 6).

5. Conclusion and discussion

Enhanced advection can occur due to spatially heterogeneous irrigation practiced in faming lands. This paper tried to examined the conditions under which enhanced advection occur, and its contribution to total evapotranspiration and CWUE in irrigated winter wheat fields in the North China Plain. We found enhanced canopy evapotranspiration induced by enhanced advection in the crop fields. Enhanced advection occurs with negative values of canopy–air temperature difference when the Priestley–Taylor parameter values >1.5. On days with enhanced advection, the average daily advective evapotranspiration can exceed 50% of the total evapotranspiration. Affected by enhanced advection, CWUE decreased remarkably due to extra water evaporated by the advected energy.

It is well known that the effects of advection on evapotranspiration are controlled by the canopy conductance. Hence, quantification of canopy conductance is important for understanding the WUE of irrigated crops. More work should be focused on the response of individual canopy leaves to environmental factors. The effects of advection on evapotranspiration have important implications for the large-scale estimation of evapotranspiration in irrigated fields of arid regions and irrigation water management. When evapotranspiration is enhanced by advection, the expected irrigation efficiency cannot be reached. When estimating evapotranspiration over large-scale irrigated fields, the effect of advection should be taken into account.

Caveats. Conclusions derived in this study is based on data collected by only one set of eddy covariance system to study advection arising out of heterogeneous conditions at multiple locations. Therefore, comparisons of energy flux between locations with differing irrigation treatments (or irrigated and unirrigated) and their contributions to the energy advection could not be verified. Further research should be focused on using multiple sets of eddy covariance systems at multiple locations to measure the fluxes in simultaneously. Further studies need be done to address these issues in a more comprehensive manner and to come-up with better conclusions and recommendations for enhancing water use efficiency in irrigated agriculture in the semiarid regions.

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