Vapor Condensation in Rice Fields and Its Contribution to Crop Evapotranspiration in the Subtropical Monsoon Climate of China

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(Manuscript received 28 October 2017, in final form 24 April 2018)

ABSTRACT

While vapor condensation in arid and semiarid areas has garnered much attention, such information is scarce for humid crop production areas such as rice fields. In a water-saving irrigation (WSI) rice field, high-precision weighed microlysimeters allowed the direct and independent quantification of condensation over plants (C_c) and soil (C_s) through mass balance calculations. The occurrence frequency and rate of C_c generally exceeded that of C_s . Predominantly occurring between sunset and sunrise, particularly between 0400 and 0500 local time, C_c showed an overall maximum rate of 0.096 mm h^{-1} . In contrast, C_s was highest between 0100 and 1100 local time and showed an overall maximum rate of 0.044 mm h^{-1} . The occurrence of C_c , unlike that of C_s , required a surface temperature lower than the ambient temperature or dewpoint. Of 65 rain-free days, C_c and C_s occurred on 60 and 33 days, respectively. Seasonal C_c , C_s , and $C_c + C_s$ were estimated as 32.3, 3.1, and 35.4 mm, respectively, and their contributions to seasonal rice transpiration T , evaporation E , and evapotranspiration (ET) were 9.5%, 1.6%, and 6.7%, respectively. The seasonal $C_c + C_s$ was similar in magnitude to a routine irrigation quota and accounted for 10.8% of rainfall and 14.4% of irrigation in the WSI rice field. Therefore, vapor condensation in rice fields in a subtropical monsoon climate is an important component of the hydrological cycle and cannot be ignored when tabulating the field water balance, calculating field water consumption, or in irrigation scheduling.

1. Introduction

Vapor condensation, including dewfall and hygroscopic water, is a process whereby water vapor from the atmosphere is cooled and condenses as a liquid on a given surface cooler than the dewpoint temperature of the surrounding air (Glenn et al. 1996; Graf et al. 2008). It is an essential meteorological process (Madeira et al. 2001; Kabela et al. 2009) and is an important component of the land surface moisture cycle (Yan and Xu 2010; Lü et al. 2011). The process of vapor condensation has drawn interdisciplinary interest from such fields as meteorology, hydrology, ecology, and agriculture (Llorente et al. 2000; Hornbuckle et al. 2006; Malek et al. 1999; Hanisch et al. 2015; Kabela et al. 2009).

Besides providing a potentially critical environmental moisture source (Zhang et al. 2007; Clus et al. 2008), particularly in arid climate ecosystems, vapor condensation also reduces crop transpiration T by temporarily creating high-humidity conditions around leaves, thereby reducing the T driving force (Singh et al. 2006; Ben-Asher et al. 2010). Moreover, it also plays a significant role in the water budget of ecosystems and in maintaining the water status of plants in both arid (Jacobs et al. 2002, 2006; Wang and Zhang 2011; Hao et al. 2012; Uclés et al. 2014; Zhang et al. 2015) and humid environments (Liu et al. 2003; Graf et al. 2004; Goldsmith et al. 2013).

Most quantifications of vapor condensation in an agriculture setting have been reported for arid or semiarid areas (Jacobs 1994; Kabela et al. 2009), where it plays an important role in water cycling between the air and the underlying crop canopy surface (Li 2002; Graf et al. 2008;

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DOI: 10.1175/JHM-D-17-0201.1

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Zhang et al. 2015). Dew measurement and dew and plant development have been discussed long ago. Many papers were cited and discussed to illustrate the dew measurement, the links between dew and plant development, and dew forecasting in the research by meteorological scientists like Wallin (1967), who was aware of the agricultural significance of dew and reported that dewfall depths vary widely around the world, reaching as high as 5 mm day^{-1} in Brazil. Throughout crop growing seasons, the frequency of occurrence of condensation generally exceeded 50% of the night periods, with seasonal condensation accounting for 5%–20% of total rainfall over the observation period (Monteith 1961; Jacobs 1994; Wilson et al. 1999; Kabela et al. 2009; Wen et al. 2012; Uclés et al. 2014; Hanisch et al. 2015). Few studies have investigated vapor condensation in rice paddies or wetlands because of the flooding and high humidity associated with these environments. In addition, no studies on vapor condensation over soil can be made in these environments since they are flooded. Luo and Goudriaan (2000) measured the vapor condensation in flooded rice fields in a tropical monsoon region using blotting paper as an absorbent, finding that the maximum daily dew amount was as high as 0.218 mm (per leaf area). Yan and Xu (2010) found that the maximum monthly vapor condensation measured using a poplar woodstick collector was approximately 1.3 mm (per leaf area) in September. Moreover, they found that the condensation density could be calculated using regressions with net radiation, ambient dewpoint temperature, the difference between surface and air temperature, and wind speed. In rice fields in Sanjiang Plain, the seasonal vapor condensation (per land surface), assessed by the poplar woodstick collector method, reached 26.2 and 31.4 mm in 2008 and 2009, and accounted for 8.68% and 6.14% of seasonal precipitation, respectively (Xu et al. 2011).

While previous studies have shown vapor condensation to occur in flooded rice fields, these measurements were made using artificial materials (e.g., absorbent), whereas direct measurements of vapor condensation from real plant and soil surfaces using precise quantification methods (e.g., weighed lysimeter) have never been undertaken. Meanwhile, to cope with increasing water scarcity, several water-saving irrigation (WSI) techniques have been recently applied to rice paddies (Belder et al. 2004; Kato et al. 2011; Rothenberg et al. 2011; Cui and Huang 2012). In WSI rice fields where air humidity is very high and soil is nonflooded during approximately half of the rice growing season, vapor condensation over the interplant soil surface may offset soil evaporation to some degree. Yet, information regarding vapor condensation over either the plant surface or soil

surface in WSI rice fields remains unclear, as well as its contribution to crop evapotranspiration.

Several methods have been used to measure the vapor condensation in various ecosystems, including soil or air moisture sensors (Moro et al. 2007; Schmitz and Grant 2009); paper and cloth drosometers (Agam and Berliner 2006; Kabela et al. 2009); artificial condensation plates made from plywood, woodsticks, plastic sheets, or polyethylene plates (Luo and Goudriaan 2000; Liu et al. 2001; Beysens et al. 2005; Ye et al. 2007; Xu et al. 2011); and remote sensing with microwave radiometers (Jackson and Moy 1999; Du et al. 2009). The microlysimeter, designed to directly measure evapotranspiration (ET) or soil evaporation E through mass balance computations (Evelt et al. 2012; Uclés et al. 2013), can also be used to measure vapor condensation over the plant surface or interplant soil surface using a water balance equation applied over a given period (Jacobs et al. 2000, 2002; Heusinkveld et al. 2006).

In the present study, custom-designed weighting microlysimeters were installed within a WSI rice field to 1) quantify the amount of vapor condensation over rice plant surfaces or interplant soil surfaces and their contribution to rice T , E , or ET and 2) discuss the atmospheric conditions that favored the occurrence of vapor condensation.

2. Materials and methods

a. Site and experiment description

Field measurements were conducted in 2015 by using weighed microlysimeters installed within a WSI rice field at the Kunshan Irrigation and Drainage Experiment Station ($31^{\circ}15'15''\text{N}$, $120^{\circ}57'43''\text{E}$). The study area, located in the Taihu Lake region of China, has a subtropical monsoon climate. Annual rainfall and annual pan evaporation (type A pan) were estimated as 1097.1 and 1365.9 mm, respectively. Average temperature and relative humidity were 24.8°C and 79.2%, respectively, during the rice growing season (July–October). The soil was hydragric anthrosol, with a bulk density of 1.30 g cm^{-3} . The soil volumetric saturated moisture θ_s , field capacity θ_f , and wilting point θ_w values are 0.502, 0.392, and $0.179 \text{ m}^3 \text{ m}^{-3}$, respectively.

Six weighed microlysimeters were installed in the WSI rice field in 2015 (Fig. 1) and were used to measure hourly E or vapor condensation over soil (Cs) and ET or vapor condensation over both plants and soil ($C_c + C_s$) based on the hourly mass change. The six microlysimeters were of two different sizes. Two of the three large microlysimeters were used to calculate ET or $C_c + C_s$ by mass balance, and one was used for load cell calibration. Each

FIG. 1. The setup of the microlysimeter system at the experiment station.

of the large microlysimeters used for mass balance calculation was composed of an inner cylinder (diameter 500 mm; height 500 mm, filled with soil to 400 mm), an outer cylinder, weighing system, data recording system, and draining apparatus. The inner cylinders were planted with rice. The inner cylinder was replaced by an object with a fixed weight of 143 kg in the large microlysimeter used for load cell calibration. The remaining three microlysimeters were small; two were used for mass balance calculation (E or C_s) without plants in the inner cylinder (diameter 300 mm; height 300 mm, filled with soil to 200 mm), and one was used for load cell

calibration with an object with a fixed weight of 28 kg. The weights of the inner cylinders or calibration weight object were recorded hourly. Detailed information about the design of the weighed microlysimeters and the field layout can be found in [Liu et al. \(2018\)](#).

Rice was transplanted into both open fields and the lysimeters with plants on 27 June 2015. Seedlings were planted at inter- and intrarow spacings of 0.23 and 0.16 m, respectively, and each lysimeter received four rice plants; the harvest date was 25 October 2015. Cultivation practices including fertilizer and pesticide application followed local practice and were applied to both the microlysimeters and the surrounding fields. Rice was irrigated according to a local WSI practice-controlled irrigation, either inside the lysimeters or in open rice fields (see [Xu et al. 2012](#)). The wetting–drying cycle process in paddy fields under WSI conditions is illustrated in [Fig. 2](#). Excessive water within the inner cylinder was drained through a 1-cm pipe and collected by a graduated cylinder in an observation well to measure its volume. Meteorological data were recorded within the WSI rice field at half-hourly intervals by sensors incorporated in an eddy covariance (EC) system (Open Path Eddy Covariance, Campbell Scientific Inc., United States) installed in the middle of the downwind portion of the field and simultaneously by an automatic meteorological station (WS-STD1, DELTA-T, United Kingdom) over a well-maintained meadow within the experiment station. Net radiation (R_n), air relative humidity (RH), air temperature (T_a), wind speed V ,

FIG. 2. Variation of soil moisture conditions and corresponding precipitation P and irrigation I under WSI; θ_r represents the relative soil moisture content, d represents the water depth during flooding, and the bar graph without I is precipitation.

FIG. 3. Time course of measured LAI during the rice growing season in 2015.

atmospheric pressure (P_a), and precipitation P were measured using both instruments. The R_n , RH , T_a , and V were measured at 1.5, 2.0, 2.0, and 2.5 m above ground surface, respectively. Simultaneously, canopy temperature (T_c), dewpoint temperature (T_d) at a height of 2.0 m, soil temperature (T_s), and volumetric soil moisture content θ (at 0.10-, 0.20-, and 0.30-m depths) were recorded in the WSI rice field by EC system sensors. The volumetric soil moisture content θ was also routinely monitored daily (0800 LT) both inside and outside the microlysimeter by time domain reflectometry (TRASE System, Soil Moisture Equipment Corporation, United States) at 0–0.2-, 0.1–0.3-, and 0.2–0.4-m depths. The soil surface temperature ($T_{s,0}$) was calculated using a harmonic method (Horton et al. 1983; Horton and Wierenga 1983) based on T_s measured at a depth of 0.10 m. The leaf area index (LAI), which influences C_c rates, was measured for five fixed plants over the full growing seasons (Fig. 3). The LAI for the days intervening between measurements was determined by linear interpolation.

b. Climatic conditions

Climatic conditions are enumerated in Table 1. In 2015, the annual rainfall P , maximum air temperature

($T_{a,max}$), minimum air temperature ($T_{a,min}$), and actual mean vapor pressure (VP) were $1067.3 \text{ mm yr}^{-1}$, 20.36°C , 13.39°C , and 1.73 kPa , respectively, closely matching the 50-yr average (1965–2014). The mean values of $T_{a,max}$ and $T_{a,min}$ from July to October 2015, namely 28.38° and 21.98°C , respectively, were also near the 50-yr average. Rainfall during the 2015 rice season was 327.6 mm , slightly less than the 50-yr mean (398.9 mm). Because the measured climatic conditions during the 2015 rice season are representative of this region, the results concerning vapor condensation should also be representative of this region.

c. Mass balance calculation for microlysimeters

Evapotranspiration, evaporation, and vapor condensation were estimated by hourly mass balance calculations for the bottom-sealed microlysimeters (Evelt et al. 2012). Assuming that nocturnal condensation never occurred simultaneously with evaporation or evapotranspiration, and ignoring the vapor condensation during the hours with irrigation, drainage, or precipitation events, the absolute value of hourly mass loss ΔM was equal to ET ($\Delta M > 0$) or $C_s + C_c$ ($\Delta M < 0$) in lysimeters with plants, and equal to E ($\Delta M > 0$) or C_s ($\Delta M < 0$, including the soil hygroscopic water) in lysimeters without plants (Allen et al. 1998; Heusinkveld et al. 2006; Ding et al. 2010). All values of the mass balance calculation were the average of the two microlysimeters with or without plants.

d. Contribution of vapor condensation to evapotranspiration

In the present study, the absolute value of positive hourly mass loss ΔM was deemed to represent ET or E , while the absolute value of negative ΔM represented $C_s + C_c$ or C_s . Yet, the water or mass balance was primarily calculated daily in the field, overlooking the occurrence of vapor condensation. The contributions of vapor condensation to rice ET or E were evaluated daily. Daily vapor condensation rates were calculated as the sum of hourly vapor condensation rates, and daily E , T ($T = ET - E$), and ET were calculated as the sum of hourly E , T , and ET . The contributions of daily vapor

TABLE 1. Climatic conditions during 50 years from 1965 to 2014 and in 2015.

	Annual		Rice season			
	1965–2014	2015	1965–2014			2015
	Mean	Mean	Mean	Max	Min	Mean
$T_{a,max}$ ($^\circ\text{C}$)	20.19	20.36	28.48	30.86	26.11	28.38
$T_{a,min}$ ($^\circ\text{C}$)	13.35	13.39	21.73	23.28	20.33	21.98
VP (kPa)	1.76	1.73	2.68	2.8	2.43	2.57
P (mm)	1156.8	1067.3	398.9	896.5	115.4	327.6

condensation to evapotranspiration, namely, contributions of C_c to T , C_s to E , and $C_c + C_s$ to ET , were calculated. To reveal the impact of vapor condensation on the water budget in the WSI rice field, daily ET or E ignoring vapor condensation and revolatilization were calculated as the sum of hourly mass change ΔM (including both positive values as ET or E and negative values as $C_c + C_s$ or C_s) and were referred to as ET^* and E^* ($T^* = ET^* - E^*$), respectively. Thus, ET was the total water loss and equaled ET^* plus the condensed water that was evaporated again in the morning hours. The relationship and difference between ET and ET^* is shown in Fig. 4. It shows a simplified midnight-to-midnight time course of total weight.

e. Occurrence conditions and frequency analysis

Times of C_c and C_s occurrence data served in calculating their frequency of occurrence and identifying the conditions of occurrence of vapor condensation. The dataset included the measured values of RH, wind speed V , T_a , T_c , ambient T_d , and T_s . Differences in $T_c - T_d$ or $T_c - T_a$ were analyzed when determining the criteria of C_c occurrence, while differences in $T_{s,0} - T_d$ or $T_{s,0} - T_a$ were analyzed when discussing the criteria of C_s occurrence. For each variable included in the occurrence condition analysis, values were ranked by C_c or C_s values and divided into different subsets.

Frequency distributions of C_c or C_s occurrence were analyzed either at different condensation rates or during different hours of the day. For a specific meteorological condition, the possibility of C_c or C_s occurrence for a specific range of meteorological conditions was calculated as a ratio of the number of data with C_c or C_s actual occurrence to possible times (including both occurrence and nonoccurrence times) under a specific range of meteorological condition during the rice season.

3. Results

a. Occurrence of vapor condensation in WSI rice fields

In the WSI rice field during the 2015 rice season period, there occurred 65 days without rainfall and irrigation events. Over the growing season, vapor condensation over plant surfaces was reported for 586 h, occurring within 60 of the 65 individual days monitored, while vapor condensation over interplant soil surfaces occurred for 98 h within 33 individual days. Frequency analysis indicated that the hourly C_c rates varied from 0.002 to 0.305 mm h^{-1} , but were less than 0.08 mm h^{-1} in most occurrences (Fig. 5a). The C_c events occurred overnight from sunset (1600 LT) to sunrise (0800 LT),

FIG. 4. Schematic diagram of the relationship between ET and ET^* .

mostly between 2100 and 0600 LT. Hence, the daily timeframe for C_c occurrence was 16 h (i.e., 8 h day^{-1} were dew-free), which concurred with the results of studies examining upland fields (Malek et al. 1999; Kabela et al. 2009) and sparse grass vegetation (Hanisch et al. 2015). The frequency distribution of C_c occurrence by hour of the day and C_c rates by hour of the day varied similarly (Fig. 5b), achieving a maximum of 12.5% for frequency of occurrence at 0400–0500 LT and a concurrent maximum rate of 0.096 mm h^{-1} .

The soil surface beneath the rice canopy exhibited hourly C_s rates varying from 0.004 to 0.139 mm h^{-1} (Fig. 6a), with over 70% of occurrences falling within the range of 0.01–0.03 mm h^{-1} . The frequency distribution of C_s occurrences over the hours of the day and the C_s rate also varied in a similar pattern (Fig. 6b), though both differed in magnitude from values for C_c . The time frame for C_s occurrence time was from 0100 to 1100 LT, with the greatest occurrence between 0600 and 0800 LT. A 10-h stretch of C_s occurrence is longer than that reported by Verhoef et al. (2006) over bare soil in an olive grove, but shorter than that reported by Zhang et al. (2015) over farmland in a semiarid region. Both the occurrence frequency and average C_s rates increased suddenly around sunrise and reached their maximums (21.6% and 0.044 mm h^{-1} , respectively) between 0700 and 0800 LT. This might be explained by the vapor condensation rates over soil incorporating the amount of hygroscopic water by soil after sunrise (Verhoef et al. 2006; Zhang et al. 2015), which occurs when $T_s > T_d$ and the RH of the soil's pores is lower than that of the air (Agam and Berliner 2006).

b. Diurnal pattern of hourly vapor condensation in different rice growth stages

Drawing on data on the diurnal pattern of hourly vapor condensation rates over four consecutive rain-free days in each month from July to October 2015, the diurnal variation of C_c and C_s , together with the

FIG. 5. Frequency distribution of (a) Cc and (b) condensation over the hour of the day.

surface to dewpoint temperature difference ($T_c - T_d$, or $T_{s,0} - T_d$) were plotted (Figs. 7, 8).

The value of the difference of $T_c - T_d$ varied diurnally in a unimodal bell shape, with negative values at night. The range in $T_c - T_d$ for typical days in July, August, September, and October were from -0.22° to 11.84°C , from -0.77° to 8.02°C , from -1.11° to 12.46°C , and from -2.16° to 13.14°C , respectively, while the mean daily Cc rates for these months were 0.283 , 0.334 , 0.772 , and $0.670 \text{ mm day}^{-1}$, while Cc durations were 5.8 , 7.8 , 11.5 , and 10.3 h day^{-1} . Vapor condensation over rice plants has generally been found to occur at night (Kalthoff et al. 2006; Zhang et al. 2015), when $T_c < T_d$ (Fig. 7). In the present case it also occasionally occurred when $T_c - T_d$ dropped suddenly, even if $T_c > T_d$. For example, Cc occurred when the value of $T_c - T_d$ was near or smaller than 0°C (e.g., 0200–0600 LT 26 July, 0400 LT 27 July, 0300–0600 LT 28 July, and 0500 LT 29 July), or during a sudden drop in $T_c - T_d$ (e.g., 2000 LT 26 July, 2000 LT 27 July, 1900–2000 LT 28 July, and 1900–2200 LT 29 July). The number of hours in August when $T_c - T_d < 0^\circ\text{C}$ was greater than in July, as was the frequency of occurrence of Cc events. In September and October, the negative amplitude of $T_c - T_d$ was greater than that in July and August, and the duration of periods

of nocturnal negative $T_c - T_d$ values was prolonged. The hourly Cc rates and frequency of Cc occurrence in these fall months were highest between 0600 and 1100 LT.

For Cs events (Fig. 8), both hourly Cs rates and their frequency of occurrence were much lower than for Cc events. In June, the LAI and canopy cover ratios were low; the soil beneath the rice canopy received more solar radiation during the day, which resulted in soil heating. In addition, the difference of $T_{s,0} - T_d$ varied from 1.69° to 12.65°C , (i.e., $T_{s,0} > T_d$); as a result, no Cs event occurred. On typical days in August–October, $T_{s,0} > T_d$, while condensation over soil occurred occasionally. In August (Fig. 8a), Cs rates were low and occurred between 0300 and 0600 LT occasionally. The Cs rates then increased in September, and the occurrence time was slightly delayed (0400–0800 LT; Fig. 8b). The rates and the frequency of occurrence of Cs increased further in October (Fig. 8c), with an average daily amount of $0.152 \text{ mm day}^{-1}$, which primarily occurred from 0600 to 1100 LT. Differences in θ might have led to the difference in Cs rates between August and September–October. On typical days in August [days after transplanting (DAT) = 62–65 days] and September (DAT = 74–77 days), $\theta_r > 85\%$ (as listed in Fig. 2), and the Cs rates were low. Yet, in October

FIG. 6. Frequency distribution of (a) Cs and (b) condensation over the hour of the day.

FIG. 7. Diurnal variation of hourly C_c and the corresponding temperature difference between T_c and T_d in (a) July, (b) August, (c) September, and (d) October.

(DAT = 111–114 days), θ_r was relatively low, and the C_s rates were much higher.

c. Seasonal variation of daily vapor condensation

The daily vapor condensation rates of C_c and C_s in the WSI rice field during the rice season are shown in Fig. 9. In the WSI rice field, C_c events occurred in 60 out of the 65 rainless days (92.3%), while C_s events occurred in 33 of the 65 days (50.8%). Daily C_c and C_s rates varied from 0.086 to 1.128 mm day⁻¹ and from 0.020 to 0.178 mm day⁻¹, respectively, with seasonal totals of 32.276 and 3.132 mm, respectively. Over the season's 65 rain-free days, the daily $C_c + C_s$ rate was 0.545 mm day⁻¹, with a maximum value of 1.227 mm day⁻¹ on 12 October 2015. These $C_c + C_s$ rates were much greater than those reported for grasslands and sparse shrubs (0.1–0.2 mm day⁻¹; Jacobs et al. 2006; Moro et al. 2007), and the C_c rates were much higher than those reported under corn (0.01–0.6 mm) and soybean (0.003–0.8 mm day⁻¹) cultivation in arid and semiarid environments (Kabela et al. 2009).

As in the study of Zhang et al. (2015), in the present study of a WSI rice field, daily C_c rates and frequencies of occurrence in the fall (September and October) were

greater than those in the summer (July and August). Besides the difference in micrometeorological conditions between midsummer and fall, the larger late season leaf area for condensation to occur on likely also contributed to the greater C_c rates in September and October. The $C_c + C_s$ rate was greatest at the yellow ripening stage, ranging from 0.555 to 1.227 mm day⁻¹, with an average of 0.873 mm day⁻¹. The frequency of C_s events in the WSI rice field was very low in July and August and increased gradually in the fall, reaching its maximum frequency in late October. Apart from climatic conditions, this phenomenon might be ascribed to generally low θ ($\theta < \theta_j$; Fig. 2) at the yellow ripening stage, which favored the occurrence of soil hygroscopic water in the early morning under high RH (generally >95%).

d. Contribution of vapor condensation to rice evapotranspiration

The daily ET, T , and E , as well as the contributions of C_c , C_s , and $C_c + C_s$ to T , E , and ET, were assessed in WSI paddy fields (Fig. 10). On days when condensation occurred, C_c/T , C_s/E , and $(C_c + C_s)/ET$ averaged 0.142, 0.220, and 0.116, respectively, with maximum values of

FIG. 8. Diurnal variation of hourly Cs and the corresponding temperature difference between $T_{s,0}$ and T_d in (a) August, (b) September, and (c) October.

0.309 (12 October), 0.368 (14 October), and 0.276 (12 October), respectively, which appeared during the yellow maturity stage. Seasonal C_c , C_s , and $C_c + C_s$ were estimated as 32.3, 3.1, and 35.4 mm, and their contributions to seasonal T , E , or ET were 9.6%, 1.6%, and 6.7%, respectively.

At the tillering stage (from 7 July to 7 August), ET and T increased gradually, reaching their respective maxima in the late tillering stage, when the contributions of vapor condensation were minimal. The contribution of C_s/E at

this stage was close to zero, as C_s was undetectable on days preceding 15 July 2015. The C_c/T and $(C_c + C_s)/ET$ varied from 0 to 0.1, with respective mean values of 0.085 and 0.045. During the period from jointing to flowering (from 8 August to 12 September 2015), C_c/T and $(C_c + C_s)/ET$ increased with the increase in LAI. The value of C_c/T was 0.120 at jointing–booting and 0.149 at heading–flowering, while equivalent $(C_c + C_s)/ET$ values were 0.092 and 0.126, respectively. The C_s events occurred more frequently in this stage, yet its

FIG. 9. Daily C_c and C_s in the WSI rice field (P represents precipitation).

FIG. 10. Soil evaporation E , rice transpiration T , and ET , as well as the contribution of vapor condensation to E , T , and ET (Cc to T , Cs to E , and $Cc + Cs$ to ET) during the rice growing season in 2015.

contributions to E fluctuated greatly. During the milk period (from 13 September to 11 October), T , E , and the ratios of Cc/T and Cs/E varied less remarkably with mean values of Cc/T , Cs/E , and $(Cc + Cs)/ET$ of 0.156, 0.087, and 0.139, respectively. During the yellow maturity stage (12–22 October), the amount of condensation was large, whereas T , E , and ET were small. Thus, contributions of Cc/T , Cs/E , and $(Cc + Cs)/ET$ were much greater than in prior stages, with average values of 0.246, 0.199, and 0.235, respectively.

e. Condensation occurrence conditions

Many meteorological factors influence the formation and amount of vapor condensation, including the surface and air temperatures, relative humidity, and wind speed. Among these factors, the values of $T_c - T_a$ and $T_s - T_a$, RH, and wind speed V were essential factors that dominated the formation of dewfall and hygroscopic water (Figs. 11, 12).

Theoretically, Cc occurs only when T_c declines below T_a or T_d . As expected, Cc occurred when $T_c - T_a < 0^\circ\text{C}$, and the probability of occurrence of Cc was nearly 100% when $T_c - T_a < -4^\circ\text{C}$ (Fig. 11b). Regarding the temperature difference of $T_c - T_d$, Cc always occurred as expected when $T_c - T_d < 0^\circ\text{C}$. Furthermore, Cc occurred with a considerable probability even when $T_c - T_d > 0^\circ\text{C}$. For example, for approximately 47.3% and 44.4% of Cc occurrences when $0^\circ\text{C} < T_c - T_d < 1.5^\circ$ and $1.5^\circ\text{C} < T_c - T_d < 3.0^\circ\text{C}$, respectively, Cc also occasionally occurred when $T_c - T_d > 3^\circ\text{C}$ (Fig. 11a). This was attributable to the fact that T_a and T_d were measured 2 m above the soil surface, which was above the rice canopy. The dewpoint at canopy height (typically less than 1.2 m) might be higher than at 2 m, and the $T_c - T_d$, calculated based on T_d measured at 2 m might

have overestimated the actual temperature difference between the canopy and its nearest ambient air.

High ambient RH and low V favored the occurrence of vapor condensation. With RH above 60% in the subtropical monsoon climate of East China, the occurrence of a Cc event was more likely at an increased RH (Fig. 11c). The probability of a Cc occurrence exceeded 50% when $RH > 80\%$ and peaked at 70% when $RH > 90\%$. For V , the probability of Cc occurrence was greater than 50% when $V < 0.45 \text{ m s}^{-1}$ and decreased sharply to approximately 15% when $V > 0.6 \text{ m s}^{-1}$ (Fig. 11d). Notably, in the current experiment the V and RH were measured at heights of 2.5 and 2 m, respectively. Since V generally increased and RH decreased with increasing elevation, V was generally higher at 2.5 m and RH was generally lower at 2 m than their corresponding variables within the rice canopy (Uclés et al. 2014; Hanisch et al. 2015). This suggests that the threshold for Cc occurrence was higher for RH and lower for V at leaf level than for those above the plant canopy.

The conditions for the occurrence of Cs differ slightly from those for Cc : Cs occurred predominantly when $T_a > T_{s,0}$, and occasionally when $T_a < T_{s,0}$, for certain ranges of $-4.5^\circ\text{C} < T_{s,0} - T_a < 3^\circ\text{C}$. The greatest potential for occurrence existed when $-4.5^\circ\text{C} < T_{s,0} - T_a < -3^\circ\text{C}$, declining as $T_{s,0} - T_a$ increased (Fig. 12b). In the present study, Cs generally occurred when $T_{s,0} - T_d > 0^\circ\text{C}$, with the highest probability occurring when $0^\circ\text{C} < T_{s,0} - T_d < 2^\circ\text{C}$, and a roughly 50% occurrence for $2^\circ\text{C} < T_{s,0} - T_d < 5^\circ\text{C}$. As with Cc , the instances of Cs occurred under high ambient RH and low V . The possibility of Cs occurrence increased as RH increased, with a maximum probability of occurrence (20%) when $RH > 90\%$ (Fig. 12c), compared to a

FIG. 11. Probability of leaf condensation occurrence with meteorological conditions (a) $T_c - T_d$, (b) $T_c - T_a$, (c) RH, and (d) wind speed V .

lesser than 10% probability when $RH < 90\%$. Regarding wind speed (Fig. 12d), the probability of Cs occurrence was relatively high when the wind speed at 2.5 m was between 0 and 0.3 m s^{-1} , decreasing as V increased, and becoming evenly distributed among the V ranges of $0.75\text{--}1.6 \text{ m s}^{-1}$.

In contrast to the possibility of Cc occurrence under temperature conditions (Fig. 11b), Cs occurred in a greater proportion under the conditions where either $T_{s,0} - T_d$ or $T_{s,0} - T_a$ exceeded zero (Fig. 12b). The value of $T_{s,0}$ is not only sensitive to T_a , but also to the soil heat flux, whether it is heat storage or release. Included in Cs, soil hygroscopic water differs according to the conditions under which dewfall occurs over the soil surface. Compared to dewfall, soil hygroscopic water generally existed at an even wider range of temperature conditions (Verhoef et al. 2006; Zhang et al. 2015). Thus, the relationship between $T_{s,0}$ and T_a or T_d affects vapor condensation in a complex manner. The greater the RH and the lower the V , the easier it becomes for vapor condensation to occur, though the possibility of occurrence of Cs is less than that of Cc under the same conditions. Since the selected year experienced conventional meteorological conditions, these conclusions should generally be universal and representative for the region under water-saving irrigation.

4. Discussion

a. Methods for measuring vapor condensation in paddy fields

Past measurements of vapor condensation onto rice leaves has been undertaken with artificial absorbents such as blotting paper (Luo and Goudriaan 2000) or woodsticks (Yan et al. 2010). However, hairs on either side of rice leaves favor the formation of water droplets, such that Cc measured using artificial absorbents likely underestimates the real Cc. Because of the flooding conditions in traditional rice paddy cultivation, one cannot distinguish condensation over soil from hygroscopic water from soil. The present study was the first attempt to measure vapor condensation over rice and soil (including soil hygroscopic water) separately. By using high-precision-weighed microlysimeters, the actual amount of condensation onto rice plants and soil was measured separately and directly in WSI rice fields. This method is therefore more suitable for paddy fields than those reported previously.

In the current study, to ensure the accuracy of microlysimeter measurements, the soil depth in the microlysimeters extended to 0.40 m, which was chosen as it matched the maximum root length of rice. In

FIG. 12. Probability of soil surface condensation occurrence with meteorological conditions (a) differences between soil surface temperature and atmospheric dewpoint, (b) differences between soil surface and air temperature, (c) RH, and (d) wind speed.

addition, to match the in situ field environment and reduce boundary effects, the lysimeters were buried in the soil and surrounded with rice plants in all directions. All sensors used in the current research were calibrated to ensure their accuracy, and a special lysimeter with a fixed weight was used to eliminate sensor creep effects. Measurements of ET with the weighed microlysimeters closely matched measurements made with an eddy covariance system (Liu et al. 2018). Because of the boundary effect over small-sized lysimeters, the rice ET measured by microlysimeters was slightly higher than that obtained by eddy covariance, a method considered to underestimated rice ET due to an energy closure deficit. Therefore, the weighed microlysimeters were deemed to have accurately measured vapor condensation over the WSI rice fields, and only slightly overestimate ET because of the boundary effect. Accordingly, the contribution of vapor condensation to rice evapotranspiration in WSI paddy fields may have been underestimated in current research.

b. Analysis of Cs occurrence links with environment conditions

Generally occurring during sudden drops in $T_{s,0} - T_d$ within a range of $0^\circ\text{--}6^\circ\text{C}$, Cs events were more common when $T_{s,0} > T_d$. Similar results were reported by

Heusinkveld et al. (2006), who observed that the dew formation process began when $T_{s,0} - T_d > 10^\circ\text{C}$. Several studies have shown vapor condensation or hygroscopic water to be formed when $T_{s,0} > T_d$ (Agam and Berliner 2004; Graf et al. 2004; Pan et al. 2010). This phenomenon can be partially ascribed to differences in temperature observation elevations. In the present study the T_d was measured 2 m above the ground surface, such that T_a and RH at that height were lower than that at soil surface during the process of heat release from soil. This suggests that the temperature difference $T_{s,0} - T_d$ overestimated the real temperature difference between $T_{s,0}$ and T_d near the soil surface. Meanwhile the high air RH ($>90\%$) and low θ in rice fields favored the occurrence of soil hygroscopic water, which also accounted for the occurrence of Cs events when $T_{s,0} > T_d$.

As the surface area of the rice crop canopy is large during most of the season, hourly Cs rates were much lower than Cc rates (Figs. 5–8). Diurnal variation analysis showed the onset of Cc to occur at sunset or slightly before sunset, whereas that of Cs occurred only after midnight in the early morning. This is likely attributable to the difference in canopy air and surface soil cooling processes. The canopy air temperature dropped sharply at sunset and quickly approached the dewpoint, whereas

TABLE 2. The main water balance components in the WSI paddy field (mm).

Input terms				Output terms		
Precipitation P	Irrigation I	Condensation water ($Cc + Cs$)		Drainage Q	Evapotranspiration (ET)	
		Canopy (Cc)	Soil (Cs)		Evaporation E	Transpiration T
327.6	246.4	32.3	3.1	85.0	187.9	341.1

changes in $T_{s,0}$ always lagged behind those of T_a , such that soil heat storage was released slowly over the several hours after sunset (Masseroni et al. 2015; Liu et al. 2018). This explains why, in rice fields, Cs events occurred much later than Cc events.

c. Importance and contribution of vapor condensation to the rice field water budget

While vapor condensation was well recognized as an important hydrometeorological process and water balance component in arid or semiarid areas, information on vapor condensation in humid areas was scarce. The seasonal vapor condensation rate in the WSI paddy field under a subtropical monsoon climate (32.28 mm over rice canopy and 3.132 mm over soil) was higher than most results measured in upland fields. For example, annual vapor condensation in a dry desert valley of central Utah was measured at 29.31 mm (Malek et al. 1999) and at 33 mm in the western Negev Desert in Israel (Kidron et al. 2002). The quantity of seasonal vapor condensation measured in the present study was roughly two- to threefold greater than recorded for corn and soybean fields (Yan et al. 2010) and slightly greater than the amounts reported for a rice field in a humid temperate zone in northeastern China ($Cc = 26.2$ mm; Yan et al. 2010). This indicates that vapor condensation in rice fields in a subtropical monsoon climate is also an important water balance component and cannot be ignored.

The magnitude of water balance components in WSI paddy fields from tillering to yellow ripening are shown in Table 2. Seasonal rainfall and irrigation were 327.6 and 246.4 mm, respectively. The seasonal condensation, $Cc + Cs$, was 35.4 mm, under average hydrometeorology conditions and close to a routine irrigation quota. In this year, $Cc + Cs$ accounted for 10.8% of the rainfall and 14.4% of the seasonal irrigation, highlighting the fact that water vapor condensation represents an important source of water in WSI paddy fields in the humid climate.

Transpiration T and ET over the season, including the revolatilization of vapor condensation over the soil surface or canopy surface, totaled 341.1 and 529.0 mm, respectively (Table 2). When daily ET was determined by either the daily water balance calculation (Liu et al. 2018) or a daily energy balance calculation (Kalthoff et al. 2006), both Cc and Cs and their revolatilization

were ignored in the calculation of T and ET (termed as T^* and ET^*). For the WSI rice field under study, seasonal T^* and ET^* were estimated at 308.8 and 493.6 mm, and the contributions of Cc/T^* and $(Cc + Cs)/ET^*$ were 10.4% and 7.2%, respectively, thereby underestimating the rice crop's actual water requirements by 9.5% and underestimating the rice ET by 6.7%. However, if the evapotranspiration is measured at an hourly scale using a micrometeorology method (e.g., eddy covariance), the measured daily ET is actually the paddy field's water consumption. That 6.7% of the daily crop ET came from revolatilization of the vapor condensation was previously unknown. Since vapor condensation was ignored in determining daily rice ET based on a daily water balance calculation, and in the irrigation scheduling to determine the appropriate irrigation volume, the irrigation demand was the same result whether or not a vapor condensation event was considered. Yet, this overlooked an important hydrometeorological component of the energy balance and underestimated the real crop water consumption capacity. Thus, quantifying vapor condensation is important in understanding the rice field's hydrometeorological and hydrological cycles, and it can be considered as a "free" form of irrigation, although it did not influence the result of irrigation scheduling based on daily water balance calculation.

5. Conclusions

Vapor condensation over plants (Cc) and soil (Cs) in WSI rice fields was measured separately using high-precision-weighed microlysimeters and mass balance calculation. This method is suitable for vapor condensation measurement in rice fields. Both the frequency of occurrence and magnitudes of Cc events were greater than those of Cs events. The Cc events occurred from sunset to sunrise, with a maximum rate of 0.096 mm h^{-1} occurring between 0400 and 0500 LT. Comparatively, Cs events occurred from 0100 to 1100 LT, with a maximum rate of 0.044 mm h^{-1} between 0700 and 0800 LT. The Cc events occurred not only when $T_c < T_d$, but also occasionally during sudden drops in $T_c - T_d$, even when $T_c > T_d$. Instances of Cs events generally occurred during a sudden drop in $T_{s,0} - T_d$, although in most cases $T_{s,0} > T_d$. The probability of occurrence of a

Cc event was nearly 100% when $T_c - T_a < -4^\circ\text{C}$ or $T_c - T_d < 0^\circ\text{C}$. Overall, Cs events, including soil hygroscopic water, occurred in a larger proportion under conditions where $T_{s,0} - T_d > 0$ or $T_{s,0} - T_a > 0$. Other than surface temperature, high ambient air humidity and low wind speed favored the occurrence of vapor condensation.

Over the growing season, Cc events occurred in 60 out of the 65 rain-free days (92.3%), whereas Cs occurred in 33 of the 65 days (50.8%). The rates of Cc and Cs and their frequency of occurrence were greater in the fall than in the summer. For the present study's WSI paddy field subject to a subtropical monsoon climate, the seasonal cumulative Cc and Cs were estimated as 32.3 and 3.1 mm, respectively, higher than most results measured in upland fields. Their contribution to seasonal T and E were 9.5% and 1.6%, respectively.

Accordingly, overlooking vapor condensation in WSI rice fields could underestimate the water consumption capacity in rice fields by 6.7%. Vapor condensation in rice fields in a subtropical monsoon climate is an important component of the hydrological cycle and must accordingly be accounted for in the condensation and revolatilization process, as well as in the calculation of field water consumption and irrigation demand.

Acknowledgments. This work was supported by the National Key R&D Program (2017YFC0403200), the Fundamental Research Funds for the Central Universities (2018B00414), the National Natural Science Foundation of China (51579070, 51479210), Jiangsu Province Water Conservancy Science and Technology Project (2015088), and the Priority Academic Program Development of Jiangsu Higher Education Institutions.

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