Seasonal and Interannual Variations in the Surface Energy Fluxes of a Rice–Wheat Rotation in Eastern China

Zexia Duan,a C. S. B. Grimmond,b Chloe Y. Gao,c Ting Sun,b Changwei Liu,a Linlin Wang,c Yubin Li,a and Zhiqiu Gao,a,d

a Climate and Weather Disasters Collaborative Innovation Center, School of Atmospheric Physics, Nanjing University of Information Science and Technology, Nanjing, China
b Department of Meteorology, University of Reading, Reading, United Kingdom
c Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, New Jersey
d State Key Laboratory of Atmospheric Boundary Layer Physics and Atmospheric Chemistry, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

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ABSTRACT: Quantitative knowledge of the water and energy exchanges in agroecosystems is vital for irrigation management and modeling crop production. In this study, the seasonal and annual variabilities of evapotranspiration (ET) and energy exchanges were investigated under two different crop environments—flooded and aerobic soil conditions—using three years (June 2014–May 2017) of eddy covariance observations over a rice–wheat rotation in eastern China. Across the whole rice–wheat rotation, the average daily ET rates in the rice paddies and wheat fields were 3.6 and 2.4 mm day−1, respectively. The respective average seasonal ET rates were 473 and 387 mm for rice and wheat fields, indicating a higher water consumption for rice than for wheat. Averaging for the three cropping seasons, rice paddies had 52% more latent heat flux than wheat fields, whereas wheat had 73% more sensible heat flux than rice paddies. This resulted in a lower Bowen ratio in the rice paddies (0.14) than in the wheat fields (0.4). Because eddy covariance observations of turbulent heat fluxes are typically less than the available energy (Rn – G; i.e., net radiation minus soil heat flux), energy balance closure (EBC) therefore does not occur. For rice, EBC was greatest at the vegetative growth stages (mean: 0.90) after considering the water heat storage, whereas wheat had its best EBC at the ripening stages (mean: 0.86).

KEYWORDS: Energy budget/balance; Evapotranspiration; Fluxes

1. Introduction

Land–atmosphere exchanges of energy and mass play a crucial role in hydrological, climatological, and biological processes (You et al. 2017). Our understanding of these processes largely relies on observations from eddy covariance (EC) flux measurement towers (Stoy et al. 2013). The EC technique is considered to be the most direct and trustworthy method to monitor soil–plant–atmosphere carbon, water, and energy fluxes (Baldocchi 2003).

Many meteorological and air-quality models are especially sensitive to the seasonal variations in surface energy partitioning of available energy into sensible heat flux H and latent heat flux αE (Bi et al. 2007; Hossen et al. 2012). Based on successive EC measurements of water and energy fluxes, seasonal and interannual energy partitioning and evapotranspiration (ET) in agricultural areas have considered winter wheat (Schmidt et al. 2012; Eshonkulov et al. 2019), winter wheat–summer maize rotation cropland (Lei and Yang 2010), cotton (Onceley et al. 2007), and rice paddies (Gao et al. 2003; Tsai et al. 2007; Alberto et al. 2009; Hossen et al. 2012; Timm et al. 2014; Masseroni et al. 2015). Previous studies have reported that the partitioning of the net radiation Rn into αET, H, and soil heat flux G is closely related to meteorological factors (e.g., solar radiation, temperature, and moisture) and biological factors (e.g., plant functional type, phenology, and stomatal regulation) (Ding et al. 2013; Jia et al. 2016). In recent decades, intense human activities and agronomic measures (e.g., irrigation methods, crop rotation, and changes in soil fertility) have dramatically affected the ecological and hydrological processes of agricultural areas, including energy partitioning, aerodynamic characteristics, soil water content, ET, and carbon sequestration (Liu et al. 2019). Despite efforts to investigate the surface partitioning of the available energy into H and αET, there is still considerable uncertainty regarding the magnitude of the energy fluxes from rice–wheat rotation ecosystems in eastern China.

Rice–wheat rotation, with two crops per year, increases crop yield and land-use efficiency (Lan et al. 2020). This ubiquitous rotation in East and Southeast Asia (e.g., India, Nepal, China), covering ~26 million ha (Timsina and Connor 2001), provides a stable food source for more than 20% of the world’s population (Kumari et al. 2011). Thus, it is significant to regional and global food security (Jin et al. 2020). Surface–atmosphere exchanges differ between rice paddies and wheat because of the paddy water regime. The common practice for rice involves flooding the field, alternating with midseason aeration, and draining before harvest; whereas for wheat, a regime of trenching and draining is used to prevent flood
damage (Zhao et al. 2009). The unique water management scheme with several dry–wet cycles causes large changes in ET and energy partitioning during the two crop seasons.

Hence, exploring these ET and energy partitioning variations is important for a better understanding of regional climate, irrigation scheduling, and modeling crop production (Ma et al. 2015; Yan et al. 2015). In the present work, a rice–wheat crop rotation in eastern China was studied using three years of heat and water EC flux measurements. The objectives were to 1) quantify the seasonal and interannual variations in surface heat fluxes (radiative, turbulent, and ground heat) to characterize the differences between the rice and wheat growing seasons, and 2) explore the dynamics of ET, energy partitioning, and energy closure over the rice–wheat rotation cropland.

2. Methods

\( a. \) Study site

A 300 m × 300 m site in Dongtai County, Jiangsu Province, China (Fig. 1a; 32.76°N, 120.47°E; 2 m above sea level), situated approximately 45 km west of the East China Sea, was used in this study. The subtropical monsoon climate has a mean annual (1984–2013) air temperature of 15.1 °C and precipitation of 1060 ± 268 mm (WMO station: 58251, i.e., Dongtai Station; Ge et al. 2018).

The site is relatively flat, with predominantly clay soils. Summer rice paddy and winter wheat grew in the fetch of the EC instruments (90% probable footprint; section 2d). Three crop years (2014/15, 2015/16, and 2016/17) were studied, each with a rotation of summer rice and winter wheat cultivated in the field around the EC tower (section 2b).

For rice cultivation (Table 1) the field was prepared in early June by flooding, plowing, and harrowing to incorporate the straw residue from the previous wheat crops prior to the field being leveled. A local midseason japonica rice cultivar (Huaidao 5) was sown in the seed bed in mid-May. In mid-June, 30-day-old seedlings were transplanted using a mechanical transplanter with a spacing of 0.25 m × 0.13 m. Nitrogen fertilizer (urea) was applied at a rate of 200 kg ha⁻¹ for the rice growing season. The ~150-day rice growing season had three stages: vegetative (Fig. 1c), reproductive (Fig. 1d), and ripening (Fig. 1e) (South Shen Zao Zhen: local agrotechnical station; M. Xu 2018, personal communication). At the beginning of the vegetative stage, the rice field was kept saturated but not flooded so as to allow the rice seedlings to recover from transplantation shock. Then, the rice field was kept flooded with 0.15 ± 0.05 m of standing water until late August. Afterward, the field was flooded intermittently (water depth: ~0.05 m) until 5 weeks before harvest. Then the floodwater was naturally drained from the field until the harvest in mid-November. The irrigation water was from the surrounding rivers.

The 200-day “Yangmai 16” variety winter wheat growth period extended from late November sowing to harvest in late May the next year (Table 1). Nitrogen fertilizer (urea) was applied at a rate of 180 kg ha⁻¹. The three growth stages were related to wheat phenology: vegetative (Fig. 1f), reproductive (Fig. 1g), and ripening (Fig. 1h). Wheat was directly seeded in well-drained and nonpuddled soils and grew under unsaturated soil moisture conditions during most crop growth periods. The combine harvester, used for both crops, left all of the rice straw and wheat residues on the field.

\( b. \) Instruments and data processing

The EC technique (Fig. 1b) allows scalar fluxes to be measured within the atmospheric surface layer, enabling quasi-continuous long-term measurements with minimal disturbance to the ecosystem. For this study, a three-dimensional sonic anemometer (Campbell Scientific, Inc., CSAT3) and a CO₂/H₂O open-path gas analyzer (LI-COR Biosciences, Inc., LI-7500) were mounted 10 m above ground level (AGL) and sampled at 10 Hz.

Other sensors measured air temperature and humidity (Vaisala, Inc., HMP45A), wind speed and wind direction (Met One, Inc., 034B), all at 3.5, 8, and 10 m AGL, and a four-component net radiometer (Kipp and Zonen, Inc., CNR-4) was at 3 m AGL. These variables were sampled at 1 Hz using a Campbell Scientific CR3000 datalogger and averaged to 30 min. The G (using Hukseflux Thermal Sensors HF01 heat flux plates), soil temperature (Campbell Scientific PT100), and soil water content (Campbell Scientific CS616) were measured at 0.05, 0.1, 0.2, and 0.4 m below the ground surface. In addition, surface atmospheric pressure (Vaisala PTB110) and precipitation (Campbell Scientific TE525MM) were observed. More details about the instruments can be found in Li et al. (2017).

The raw 10-Hz EC data were obtained with the Campbell Scientific LoggerNet 4.2.1 software and transformed into 30-min binaries. These were processed using LI-COR EddyPro 5.2.1 software into half-hourly fluxes. The data processing included averaging and statistical tests (Lee et al. 2004), time lag compensation, double rotation for tilt correction, spectral corrections (Moncrieff et al. 2004), and compensation for density fluctuations (Webb et al. 1980). The EddyPro quality flags ranged from “best” (flag 0) to “suitable for general analysis” (e.g., annual budgets) (flag 1) to “discard” (flag 2). As EC systems are unable to measure in rainy or foggy conditions, data collected under such conditions were excluded. Other data losses occurred when switching data storage cards and power outages (e.g., large data gap in 2017).

The 8-day leaf area index (LAI) data from June 2014 to May 2017 were from the MODIS MOD15A2H with 500-m resolution. [These MODIS data can be downloaded from the NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC, https://lpdaac.usgs.gov) at the USGS Earth Resources Observation and Science (EROS) Center].

\( c. \) Radiation and surface energy fluxes

When the storage heat flux of the canopy is not explicitly addressed, the surface energy balance for a crop canopy can be written (Burba et al. 1999)

\[
R_{\text{a}} = H + \lambda ET + G + \epsilon,
\]
FIG. 1. (a) Map showing the location of the Dongtai County study site (pink star) within eastern China, with the inset map showing the rice–wheat rotation area in China. (b) The 10-m observation tower (6 Mar 2016) with wheat (N = north). The main growth stages (Table 1; vegetative, reproductive, and ripening) of the (c)–(e) rice paddies and (f)–(h) wheat fields.
where $R_n$ is the net radiation (positive flux toward the surface); $H$ and $\lambda ET$ are the turbulent sensible and latent heat fluxes (positive away from the surface), respectively; $G$ is the soil heat flux (positive flux into the soil) at the surface; and $\varepsilon$ is residual energy involved in other processes, such as canopy heat storage, photosynthesis, respiration, and advection. All terms have units of watts per meter squared.

The $R_n$ consists of both incoming (↓) and outgoing (↑) shortwave radiation $K$ and longwave radiation $L$:

$$R_n = K_↓ + L_↓ - K_↑ - L_↑.$$  \hspace{1cm} (2)

The $H$ and $\lambda ET$ are calculated from the EC observations with (Kaimal and Finnigan 1994; Burba 2013; Zhang et al. 2016)

$$H = \rho c_p w' T'$$  \hspace{1cm} (3)

and

$$\lambda ET = \lambda \frac{M_w / M_d}{P} \overline{w' e' v''},$$  \hspace{1cm} (4)

where $w'$, $T'$, and $e'$ are the turbulent fluctuations from the mean of the vertical wind velocity (m s$^{-1}$), air temperature (K), and water vapor pressure (hPa), respectively; $\rho$ is the air density (kg m$^{-3}$); $c_p$ is the specific heat capacity of air at constant pressure (J kg$^{-1}$ K$^{-1}$); $\lambda$ is the latent heat of vaporization (J kg$^{-1}$); $M_w$ and $M_d$ are the water and air molar mass (g mol$^{-1}$); $P$ is the air pressure (hPa); and $ET$ is the crop evapotranspiration (mm s$^{-1}$). The three-dimensional sonic anemometer original records (10 Hz) were processed prior to analysis using the methods in section 2b.

Because of the lack of water temperature measurements, the temperature variation at a depth of 0.05 m was used to compute the water heat storage (Timm et al. 2014). Thus, $G_w$ was estimated through the sum of $G$ at a depth (of the heat flux plate) of 0.05 m ($G_{0.05}$) and the soil and water heat storage $G_w$:

$$G = G_{0.05} + C_s \Delta T_{0.05} + G_w$$  \hspace{1cm} (5)

and

$$G_w = C_s \Delta z_0 \left( \frac{\Delta T_{0.05}}{\Delta T} \right).$$  \hspace{1cm} (6)

where $C_s$ is the volumetric heat capacity of the soil (J m$^{-3}$ K$^{-1}$) and $C_w$ is the volumetric heat capacity of water (4.186 $\times$ 10$^3$ J m$^{-3}$ K$^{-1}$). The $\Delta T_{0.05}$ is the change in soil temperature at the depth of 0.05 m during the 30-min measurement period $\Delta t$, $\Delta z_0$ is the thickness of the soil layer to the surface (i.e., 0.05 m), and $\Delta z_w$ is the depth of the water layer (i.e., 0.15 m at the rice vegetative stages and 0.05 m at the rice reproductive stages; section 2a). The $G_w$ appears during the soil flooding (i.e., rice vegetative and reproductive stages in Fig. 1).

The $\varepsilon$ term [or size of the lack of energy balance closure (EBC)] was assessed using two methods. First, across multiple 30-min periods, the ordinary linear regression slope between the sum of turbulent heat fluxes ($H + \lambda ET$) and the available energy ($R_n - G$) was determined. Here, the slope was forced through 0. Second, the EBC ratio (EBR) was calculated from the 30-min data for periods of observation (Cui and Chui 2019):

$$EBR = \frac{H + \lambda ET}{R_n - G}.$$  \hspace{1cm} (7)

d. Stability and footprint analysis

The Obukhov length $L$ can be derived from (Stull 1988)

$$L = \frac{-u''}{k(z/m) w'' \theta},$$  \hspace{1cm} (8)

where $u''$ is friction velocity (m s$^{-1}$), $\theta$ is the potential temperature, $k$ (=0.4) is the von Kármán constant (Paulson 1970), and $g$ (=9.8 m s$^{-2}$) is the acceleration of gravity.

The dimensionless atmospheric stability parameter $\xi$ was calculated according to Stull (1988), as follows:

$$\xi = \frac{z' L}{\Delta T},$$  \hspace{1cm} (9)

where $z' = z_m - z_d$, in which $z_m$ is the observation height of the sonic anemometer (10 m) and $z_d$ is the zero-plane displacement height estimated using the Martano (2000) approach (details are in Text S1 in the online supplemental material). We used three $\xi$ classes: 1) stable ($\xi \geq 0.01$), 2) neutral ($\xi < 0.01$), and 3) unstable ($\xi \leq -0.01$).

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**TABLE 1. Main crop growth stages and corresponding mean canopy height $z_H$ during 2014–17 (from in situ measurements).**

<table>
<thead>
<tr>
<th>Year</th>
<th>Crop cover</th>
<th>Growth status</th>
<th>Vegetative</th>
<th>Reproductive</th>
<th>Ripening</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wheat</td>
<td>Duration 15 Dec–28 Feb</td>
<td>1 Mar–15 Apr</td>
<td>16 Apr–31 May</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wheat</td>
<td>Duration 10 Dec–29 Feb</td>
<td>1 Mar–16 Apr</td>
<td>17 Apr–25 May</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wheat</td>
<td>Duration 14 Dec–28 Feb</td>
<td>1 Mar–14 Apr</td>
<td>15 Apr–31 May</td>
<td></td>
</tr>
</tbody>
</table>
The Kljun et al. (2015) two-dimensional flux footprint tool (http://geography.swansea.ac.uk/nkljun/ffp/www/; last accessed 17 July 2018) is applicable to conditions when $\mathbf{u}^* > 0.1 \text{ m s}^{-1}$ and $z > 15.5$. It requires $z_m$, aerodynamic roughness length $z_0$, method of Martano (2000)—see Text S1], $z_d$ (Martano 2000), 30-min mean wind velocity $[\mathbf{u}(z_m); \text{m s}^{-1}]$, crosswind variance $\sigma_y (\text{m s}^{-1})$, $L$, and $\mathbf{u}^*$. As shown in Fig. S1 in the online supplemental material, $z_0$ changed with the growth of the rice and wheat, with the monthly median of $z_0$ varying between 0.01 and 0.08.

In the 3-yr study period, the source area that contributed 90% to the fluxes was smallest (average fetch length: 865 m) under unstable conditions (42% of all measurements) and largest (average fetch length: 1005 m) under stable conditions (46% of all measurements) (Table 2). The footprint extent for all measurements was largest toward the east. This was the dominant wind direction (Fig. 2).

From these results, we estimated the land-cover fractions retrieved from a Google Earth image on 6 February 2016. The compositions in the 70%–90% footprints of the 10-m tower were separated into two categories: impervious (including both buildings and roads) and cropland (Table 2). From the analysis of the 30-min EC 90% probable footprint (Kljun et al. 2015; section 2d) climatology during the 3-yr study period, the area observed included cropland (88%–96%) plus a small proportion of impervious surfaces (6%–12%) (Table 2), indicating that the measured fluxes were primarily contributed by the cropland.

3. Results

a. Climatological conditions

With the subtropical monsoon climate, all of the meteorological variables have a marked seasonal cycle (Fig. 3). The

![Figure 2](image-url)
mean 10-m wind speed for the three cropping years (2014/15–2016/17) was slightly higher in the winter wheat season (2.6 m s\(^{-1}\)) than the summer rice season (2.4 m s\(^{-1}\)) (Fig. 3a). The annual mean air temperature (at 10 m AGL) for the three consecutive cropping years was 11.8\(^\circ\)C, 13.1\(^\circ\)C, and 14.3\(^\circ\)C, respectively (Fig. 3b), which were lower than the 30-yr-average annual mean air temperature (section 2a) in the study area. It was much higher in the growing season of summer rice (22.1\(^\circ\)C) than that of winter wheat (11.8\(^\circ\)C).

Similar seasonal patterns were evident in the vapor pressure deficit (VPD) (Fig. 3c). The average VPD of the site was high in summer (5 hPa) and low in winter (3 hPa). Surface-level air pressure exhibited an inverse relation with air temperature (Figs. 3b,d). The annual precipitation for the 2015/16 and 2016/17 crop years were similar (1587 and 1640 mm, respectively) and larger than for 2014/15 (1226 mm) (Fig. 3e). The latter was more comparable to the 30-yr mean (section 2a). Most precipitation occurred from June to October, with the maximum daily precipitation of 321 mm on 10 August 2015 caused by Supertyphoon Soudelor.

b. Radiation and other surface energy fluxes

All four components of the radiation budget [Eq. (2)] and surface albedo were observed in this study (Fig. 4). As expected, seasonal variations in solar radiation received at the surface depended mainly on solar altitude and cloud conditions. At this site, the monthly median \(K_1\) ranged from 151 W m\(^{-2}\) in October to 825 W m\(^{-2}\) in May and the monthly median \(K_1\) ranged from 20 W m\(^{-2}\) in October to 126 W m\(^{-2}\) in May. The seasonal variations of \(L_1\) and \(L_1\)
were similar, with higher values in the summer rice growing season than in the winter wheat growing period. The July daily $L_I$ peaks were 477, 470, and 485 W m$^{-2}$ across the three consecutive years, whereas for $L_l$, these were 540, 537, and 547 W m$^{-2}$.

Surface albedo varied with surface conditions, including leaf growth. The seasonal mean albedo was larger for winter wheat (2014/15: 0.19; 2015/16: 0.20; 2016/17: 0.18) than summer rice (0.11, 0.10, and 0.09, respectively). Key influences were the flooded early rice period (June–July; Fig. 1c) and the winter (December–February) extensive bare soil period (Fig. 1f). The average bare soil albedo (0.15) was greater than that for water (0.12). Additionally, the largest daily values occurred with winter snow. The maximum observed daily mean was 0.53 (29 January 2015).

There were considerable differences in surface radiation balance between years. The annual mean albedo in 2016/17 was smaller than in the two earlier years (Table 3), with less shortwave radiation reflected into the atmosphere. The slightly smaller soil temperatures in 2014/15 were associated with the smaller $L_l$ (Table 3). Together, these factors contributed to the greater $R_n$ in 2016/17 (Table 3).

All of the energy balance fluxes varied seasonally (Fig. 5). Over the three years (1 June 2014–31 May 2017), the monthly medians varied from 110 to 592 W m$^{-2}$ for $R_n$, from 62 to 361 W m$^{-2}$ for AET, from 5 to 101 W m$^{-2}$ for $H$, and from −3 to 65 W m$^{-2}$ for $G$. In seasonal average terms, the rice paddies had 52% more AET than the wheat field. The wheat, on the other hand, had significantly more (73%) $H$ than the rice paddies. The AET and $H$ seasonal variations observed for the rice–wheat rotation were similar to other ecosystems (Bi et al. 2007; Wu et al. 2007; Gao et al. 2009). The response to phenological changes was evident, such as to the emergence of new leaves in February over the wheat field and June over the rice paddy and the rapid senescence from May for wheat and from September for rice. Other
seasonal fluctuations in $H$ and $\lambda E T$ were related to agricultural activities (e.g., choice of crop type, crop rotation, harvest time, and intermittent irrigation; section 2a). The $H$ also increased as the crop got drier before the harvest (late May–early June).  

### Evapotranspiration

Seasonal variations in the 8-day LAI and daily total ET for the 2014–17 cropping periods over the rice–wheat rotation systems are shown in Fig. 6. Mean LAI was slightly higher in the growing season of summer rice (1.3) than in that of winter wheat (1.0). For rice, peak LAI of 3.5, 5.4, and 4.2 m$^2$ m$^{-2}$ were observed during the reproductive stages (late August or early September) of 2014, 2015, and 2016, respectively. Peak LAI values for wheat were 2.7, 2.6, and 2.2 m$^2$ m$^{-2}$ in April 2015, 2016, and 2017, respectively.

The daily ET of wheat increased consistently with a concurrent gradual increase in LAI (Fig. 6a). As the wheat reached its peak LAI during the reproductive growth stages (around April), ET also reached its peak values. After the reproductive stages, wheat’s LAI started to decrease due to the canopy senescence. For rice, a high ET occurred during the vegetative stages mainly due to the higher evaporation of flooded water rather than transpiration since the plants were still small (LAI < 1; Alberto et al. 2011). The average daily ET for rice and wheat growing seasons were 3.6 and 2.4 mm d$^{-1}$, indicating a higher water consumption for rice than for wheat. Generally, rice paddies had higher ET than wheat fields, probably because of the absence of ponded water (Figs. 1c,d) and lower LAI of wheat (Fig. 6a) (Alberto et al. 2011).  

d. **Energy partitioning**

The proportion of $R_n$ used in $H, \lambda E T$, and $G (H/R_n, \lambda E T/R_n$, and $G/R_n$) varied seasonally with land surface conditions (Fig. 7). Generally, the middle of the day (1000–1600 LST)
$H/R_n$ and Bowen ratio ($\beta = H/\lambda ET$) had an inverse trend to $\lambda ET/R_n$, while EBR [Eq. (7)] had a similar trend to $\lambda ET/R_n$. The EBR was larger during the day (0.67–0.99) than during the middle of the night (2200–0400 LST; from −0.14 to 0.57). Consistent with Wilson et al. (2002) and Majozi et al. (2017), the nocturnal EBRs were less than the midday-period EBRs as the calm midnight period suppressed turbulence that was essential for the creation of eddies. Annually, the median midday $\lambda ET$ was the largest consumer of the $R_n$ (52%, 60%, and 62% of $R_n$ in 2014/15, 2015/16, and 2016/17, respectively), while the annual midday $\lambda ET/R_n$ was largest in 2016/17 given the larger precipitation in 2016/17 (section 3a). The median midday $H/R_n$ was 18%, 13%, and 15% in 2014/15, 2015/16, and 2016/17, respectively. The median midday $G/R_n$ was 15%, 9%, and 6% in 2014/15, 2015/16, and 2016/17, respectively. In the midday period, rice paddies had a higher (70%) $\lambda ET/R_n$ than the wheat (53%), because of the extensive presence of water (Fig. 1c). Thus, wheat had a larger median midday $\beta$ in the three years (0.42, 0.35, and 0.42) than rice (0.19, 0.13, and 0.10).

The $G$ during the midnight period (2000–0400 LST) was the largest component of energy. The median $G/R_n$ values varied over 97% (2014/15), 83% (2015/16), and 65% (2016/17). The radiative surface cooling was maintained by the $G$ (approximately −20 W m$^{-2}$) conducting heat back toward the surface. As expected, the median midday $\beta$ was positive (0.04–0.66). However, $\beta$ was negative in the midnight period (from −2.18 to −0.08) as small positive $\lambda ET$ (10 W m$^{-2}$) often occurred, with small negative $H$ (−10 W m$^{-2}$) values.
maintained by radiative cooling, conduction, and release of heat with condensation.

e. Energy balance closure

Here, we consider the effect of crop type and different growth stages on the EBC. The regression slope (forced through 0) was less than 1 for all growth stages (0.59–0.95), with a coefficient of determination $R^2$ between 0.60 and 0.88 (Table 4). This was consistent with the slope reported in Wilson et al. (2002), ranging between 0.53 and 0.99 and obtained from the analysis of 22 flux measurement network (FLUXNET) sites. The wheat EBC improved across the three growth stages (vegetative, reproductive, ripening; Table 4). Better EBC occurred at the vegetative stages for rice after considering the $G_w$ (Table 4). When $G_w$ was included in the energy balance closure, the slope improved from 0.75 to 0.91 and from 0.76 to 0.88 at the rice vegetative stages in 2015/16 and 2016/17, respectively.

4. Discussion

a. Comparisons of ET with other sites

To eliminate the uncertainties caused by experimental methods, we only collected ET data from studies based on EC measurements. As can be seen in Table 5, the cumulative ET for the whole rice growing season was 473 mm, which was comparable to that reported in the Taihu Lake region of China (Liu et al. 2018) and lower than that reported in the Philippines (Alberto et al. 2011, 2014) but greater than the water consumption reported in Japan (Ikawa et al. 2017) and Brazil (Timm et al. 2014). The differences in the total seasonal ET observed from the above studies may be due to the differences in agricultural production activities (such as crop type, growth periods, and irrigation), physiological characteristics (e.g., LAI) and meteorological conditions (Liu et al. 2018; Qiu et al. 2019). For example, the cumulative ET was highest at the Laguna site (499 mm; Table 5) in the Philippines, which was located in the tropical region with high air temperature (~27°C) and high VPD (~0.8 kPa). Furthermore, rice paddy (473 mm) had a higher mean growing-season ET rate than that for the wheat field (387 mm) at our site (Table 5). For winter wheat, the cumulative ET at our site was lower than the values reported in northern China (401–417 mm; Lei and Yang 2010; Zhang et al. 2013). The growth period of winter wheat in our area was shorter than that in northern China, which had an inhibited effect on crop growth and canopy coverage (Qiu et al. 2019).

The average daily ET rate for rice over the growing season was 3.6 mm day$^{-1}$, which was close to the values in the similar temperate climate zone (e.g., China, Japan, and Brazil) and higher than that in the boreal zone (2.8 mm day$^{-1}$) but was lower than that in the tropical zone (4–4.2 mm day$^{-1}$; Table 5). Also, the daily ET rate that occurred in our wheat fields was 2.4 mm day$^{-1}$, which was higher than in the arid regions in northern China. Generally, the daily ET rate gradually decreased from tropical to temperate and boreal zones, which was comparable to the findings reported in Kang and Cho (2021).

b. The effect of crop type and growth stages on EBC

Generally, EBC had a marked seasonal variation in the rice paddies and wheat fields. For wheat, EBC improved as the
growth stages progressed. During the ripening stages, wheat leaves gradually turned yellow (LAI < 2, Fig. 6) and photosynthetic rates became weaker. The energy fluxes for photosynthesis showed a lower contribution to EBC (within 2%) during the ripening phase of winter wheat (Eshonkulov et al. 2019). Furthermore, in the maturity

TABLE 4. Energy balance closure at different growth stages over the rice–wheat rotation during 2014–17 (N is the number of 30-min data points). Note that there are large data gaps in the 2014 rice vegetative and reproductive growth stages from instrument malfunction.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Year</th>
<th>Parameter</th>
<th>Vegetative</th>
<th>Reproductive</th>
<th>Ripening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td>2014</td>
<td>Slope</td>
<td>—</td>
<td>—</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$R^2$</td>
<td>—</td>
<td>—</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$N$</td>
<td>—</td>
<td>—</td>
<td>1079</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>Slope</td>
<td>0.91 (0.75)$^a$</td>
<td>0.90 (0.86)$^a$</td>
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<tr>
<td></td>
<td></td>
<td>$R^2$</td>
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<td>0.83 (0.83)$^a$</td>
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<td>Slope</td>
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<td>0.79 (0.77)$^a$</td>
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<td>$N$</td>
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<tr>
<td></td>
<td>2016/17</td>
<td>Slope</td>
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<td>0.72</td>
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<td>$R^2$</td>
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<td>2659</td>
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$^a$Rice EBC without considering the water storage heat.
phase of winter wheat, canopy heat storage (1% to available energy, Eshonkulov et al. 2019) also distinctly decreased as a result of lower plant water content (Meyers and Hollinger 2004). Our research demonstrated that \( u_w \) played a key role in improving EBC at the ripening stages. The canopy height of wheat was higher and wheat fields became more homogeneous during later crop development stages (Figs. 1f–h; Stoy et al. 2013). Higher mean \( u_w \) (>0.28 m s\(^{-1}\)) occurred during the wheat ripening stages, resulting in a stronger development of turbulence over wheat fields (Barr et al. 2006; Tanaka et al. 2008; Franssen et al. 2010). For rice, better EBC occurred at the vegetative stages. According to Timm et al. (2014), we also estimated the storage energy in water using the temperature variation at a depth of 0.05 m below the ground surface. The EBC improved by 19% during this period by adding \( G_w \). This result indicated that \( G_w \) makes a nonnegligible contribution to the surface energy balance (Hossen et al. 2012). Ikawa et al. (2017), also in a rice paddy study, reported that EBC improved by 12% after accounting for the 3-cm-depth water storage. As expected, the effect was greater at our site than the values reported in Ikawa et al. (2017) because the 15 cm of standing water at our site was deeper.

Because the EC flux was measured at a relatively high height (10 m; Fig. 1), there might also have been a possibility that the effect of large-scale transports differentiated the energy balance between summer and winter. In the presence of such large-scale organized structures, single-tower measurements must be biased, because the associated vertical energy transport is inherently not captured (Etling and Brown 1993; Mauder et al. 2020). Thus, multitower experiments and scale-crossing, spatially resolving lidar and airborne measurements with high-resolution large-eddy simulations will be considered in our future work.

### 5. Summary and conclusions

From the analysis of the seasonal and interannual variability of meteorological conditions including radiation and turbulent fluxes, ET, energy partitioning, and EBC over a rice–wheat rotation system in East China (1 June 2014–31 May 2017) were studied. The key findings are as follows:

As expected, given that wheat was grown in the winter, the summer rice growing season was warmer but also more humid and received more precipitation. For our study site, rice paddies (473 mm) had higher ET than the wheat fields (387 mm), probably due to the absence of ponded water and lower LAI of wheat. Across the whole rice–wheat rotation, the average daily ET rate in the rice paddies and wheat fields was 3.6 and 2.4 mm day\(^{-1}\), respectively. Considering the seasonal distribution of precipitation and agricultural production activities (such as crop type and irrigation), the rice paddies had 52% more ET than the wheat fields given the extensive water availability. Consequently, the wheat fields had a significantly higher Bowen ratio (0.4) than the rice paddies (0.14). During the observation period, the annual precipitation fluctuated between 1226 mm (2014/15).
and 1640 mm (2016/17), causing large annual variations in \( \lambda E T/R_n \) [annual midday (1000–1600 LST) values between 52% (2014/15) and 62% (2016/17)]. On an annual basis, for the entire rice–wheat rotation, the dominant ratio for the midday period was \( \lambda E T/R_n \) whereas nocturnally (2200–0400 LST) it was \( G/R_n \). EBC was greatest at the rice vegetative growth stages after considering the water heat storage, whereas for wheat it was greatest at the ripening stages. Overall, EBC was greater for rice (0.85) than for wheat (0.76).

These new data on intra- and interannual variations of fluxes provide a new understanding of the differences between rice and wheat growing seasons. These data will be beneficial for improving models to simulate surface energy exchanges for the extensive area of rice–wheat agroecosystems in Asian countries.

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