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Annual Cycle of Heat and CO_2 Fluxes Over an Artificial Rice Wetland in the Liaohe Delta of China

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Abstract. Seasonal variations in sensible heat flux (H_s), latent heat flux (LE), and carbon dioxide flux (F_c) during 2005 over an artificial rice wetland in the Liaohe Delta, Northeast China, were investigated using the eddy covariance (EC) technique. The results show that H_s is relatively larger (>200 W m^{-2}) in spring, whereas LE is relatively larger in summer and autumn (>500 W m^{-2}). F_c depends strongly on the status of the crops and mostly reaches about –2.0 mg CO_2 m^{-2} s^{-1} at daytime from June to September but varies around zero in the other months. CO_2 concentration is in the range of 300–500 ppm and varies similarly with F_c from June to September. The largest negative F_c values usually occur at mid-day, with values of –0.6 mg CO_2 m^{-2} s^{-1} during the early growth stage (5–8 June), –1.8 mg CO_2 m^{-2} s^{-1} during the middle growth stage (17–20 July), and approximately –0.2 to 0.3 mg CO_2 m^{-2} s^{-1} during the late growth stage (19–22 September). The cumulative CO_2 flux during 2005 was estimated to be –1570 g CO_2 m^{-2} year^{-1}, which suggests that the rice wetland in Panjin acts as a large CO_2 sink.

Introduction

Rice is cultivated intensively as a major food source and is in high demand worldwide, especially in Asia[1]. Rice wetlands influence the exchange of greenhouse gases such as water vapor, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) into and from the atmosphere[2-4] and the energy budget between the surface and atmosphere, and then regulate local climate to a certain degree[5].

Some studies have been carried out to determine carbon budget according to CO_2 and CH_4 fluxes in different paddy fields [6-10]. McMillan et al [9] indicated that CO_2 exchange over paddy fields is even more important because the radiative effect of CO_2 sequestration in paddy soils may be offset partially or wholly by that of CH_4. Therefore, it is important to investigate the seasonal and inter-annual variations in heat and CO_2 fluxes over rice wetlands [11-13].

Campbell et al [11] found a rice paddy field in Japan as a CO_2 sink from May to August in 2002, and the largest CO_2 flux of –39 g CO_2 m^{-2} day^{-1} occurred in late July, with the rice leaf area index reaching its peak. Alberto et al [13]observed that the latent heat flux (LE) increased by 20% and the sensible heat flux (H_s) decreased by 48% under the flooded soil conditions relative to those under the aerobic soil conditions over a rice field in Philippines during 2008, and the cumulative CO_2 flux during the cropping period under the flooded, and non-flooded soil conditions were –258 and –85 g C m^{-2}, respectively. Not only farming practices such as water management and tillage practices determine CO_2 exchange over rice wetlands[13-15], but various environmental factors such as water table, salinity, soil temperature, and vegetation influence it as well [1,16-17].

The Liaohe Delta (121°10′–122°30′E, 40°30′–41°30′N) is located in Northeast China, and the Liaohe Delta National Nature Reserve has been established since 1985, in order to prevent damage to different precious ecosystems including bare beach, seepweed (*Suaeda heteroptera*), common reed [*Phragmites australis (Cav.) Trin. Ex Steud*], meadow, rice paddy, maize, and woods [18]. Among these, rice paddies constitute the most important part of the artificial wetlands in the delta, with a total area of approximately 2,000 km^2 [19-20]. Very few studies have been examined the characteristics of seasonal variations in heat and CO_2 fluxes over this rice wetland.

Using the observational data of 2005 obtained from an ecosystem station located in Panjin rice wetland, this study aims to investigate the seasonal variations in heat and CO_2 fluxes over this rice wetland, to identify differences in diurnal variation in heat and CO_2 fluxes during different growing stages of rice plants, and to establish a rough estimate of the total annual F_c over the Panjin rice wetland and compare it with other rice wetlands.

Data and Methods

Site Description

A rice wetland ecosystem research station (41°11′N, 121°54′E) was established in Panjin city to conduct a long-term atmosphere-surface exchange experiment at the Panjin rice wetland. The landscape surrounding the station within the distance of 500 m was flat rice fields, with an elevation of 0–3 m above sea level. The local climate is featured as a temperate continental monsoon zone, with an annual mean air temperature of 8.6°C, a frost-free period of 170 days, wind speed of 4.3 m s^{-1}, a cumulative sunshine time of ≥2,700 hours [21]. The annual mean cumulative precipitation was 631 mm and rainfall events mostly occurring from July to September; the annual mean cumulative evaporation was 1390–1705 mm, about 2.5 times of precipitation [10]. Northerly winds are prevalent during winter, and southerly winds are prevalent during summer at the experimental site.

The soil of the rice wetland over the Liaohe Delta belongs to the seashore saline soil type, and it has organic carbon content of 2.3–2.8%, total salt content of 0.2–0.3%, and pH values of 7.3–7.8 [22]. The surface soil usually has plenty of water due to supplement of river water, underground water, and atmospheric precipitation in this region.

Crop Management

The variety of rice in this experiment was Jingguan, which is regarded as one of the brand products in the 2001 International Agricultural Fair and were planted over about 2700 km^2 area over the Liaohe Delta [22]. In this study, the growing period of rice plants lasted from broadcasting on 13 April to harvesting on 28 September 2005. The rice seedlings were transplanted outdoor fields on 21 May, approximately 3 months after the field was drained. The reproductive stage of rice growth indicated by panicle initiation began on 29 July. The ripening stage began 2 months later, and the crop was harvested on 28 September. The specific dates of 12 growth stages of the crop at the Panjin rice wetland station in 2005 are listed in Table 1. After harvest, rice straw were returned to soil.

Table 1 Various crop growth stages for the Panjin rice wetland during 2005

Stage	*Greenhouse seeding*			*Transplanting*	*Re-green*	*Tillering*
	Broadcasting	*Emerging*	*Three-leaf*			
Date	13 April	23 April	2 May	21 May	25 May	13 June
Stage	*Booting*	*Heading*	*Anthesis*	*Milk*	*Ripe*	Harvest
Date	26 July	4 August	—	21 August	27 September	28 September

Eddy Covariance (EC) Measurements

A 4.5 m high tower was located in the center of the rice field and equipped with an EC system at the top of the tower. Turbulence for wind speed and air temperature were measured by a sonic anemometer (CSAT3, Campbell Scientific, Inc., USA), and fluctuations in water molar densities, air densities, and carbon dioxide were measured by an open-path non-dispersive infrared gas analyzer

(LI-7500, Li-Cor, Inc., USA). All of the turbulent data were recorded using a data logger (CR5000, Campbell Scientific, Inc., USA) with a frequency of 10 Hz. The eddy covariance (EC) technique has been employed widely to measure fluxes in heat, water vapor, and CO_2 across various surfaces (e.g., /23-25/).

Data Processing

Turbulence measurements were taken at 30-min intervals using the software Edire from University of Edinburgh [26] and this duration was necessary for integrating the major time scales of turbulence occurring in the atmospheric surface boundary layer [27]. A 3-D coordinate rotation was applied to wind fluctuation data to set the mean vertical wind over a 30-min interval equal to zero and the procedures for removing a linear trend and WPL correction were performed when fluxes were calculated [28]. Using the measured turbulence data, fluxes such as friction velocity (u_*), sensible heat flux (H_s), and latent heat flux (LE), and CO_2 flux (F_c, mg m^{-2} s^{-1}) were calculated according to Equations (1) – (4).

$$u_* = \sqrt[4]{(\overline{u'w'})^2 + (\overline{v'w'})^2} \tag{1}$$

$$H_s = \overline{\rho} c_p \overline{\theta' w'} \tag{2}$$

$$LE = \overline{\rho} \lambda \overline{q' w'}, \tag{3}$$

$$F_c = \overline{c' w'}. \tag{4}$$

where u, v, and w are the stream-wise, cross-wind, and vertical velocity, respectively, θ is the potential temperature, q is the water vapor concentration (unit: mol mol^{-1}), c is the CO_2 mass concentration, ρ is the air density (unit: kg m^{-3}), C_p = 1004.7 J kg^{-1} °C^{-1} is the specific heat at constant pressure, and λ is the latent heat of vaporization for water (unit: J kg^{-1}). Prime symbols represents fluctuation above the 30-min mean, and overbars represent a time averaging operation over a period of 30 min.

Correction for CO_2 Flux

Nighttime values for F_c measured by EC sensors are usually less reliable than daytime F_c values because of the relatively stable air stratification during the nighttime, which prevents EC sensors from measuring the actual CO_2 exchange at the surface under calm conditions [29]. Therefore, the half-hour F_c values were dealt with strict data quality control [30]. Firstly, the significant outliers with $|F_c|$ >2.0 mg m^{-2} s^{-1} or $\left|F_c(j) - \overline{F_c}\right| > 5\sigma$ were deleted, with $\overline{F_c}$ and $F_c(j)$ being the mean value and the jth value of F_c in each season[1], respectively, and σ the standard deviation of F_c in each season. Secondly, data under weak turbulence conditions with u_* <0.10 m s^{-1} according to the average value test method [29,31] were excluded. Thirdly, the values of F_c > 0 during the nighttime were replaced by the fitting equation between F_c and air temperature at night [29]. Additionally, small gaps (< 2 h) and large gaps (> 2 h) except for the long gaps (> 10 days) in October and December, were filled by the same method in [32], according to [33].

Results and Discussions

Seasonal Variations in Heat and CO_2 Fluxes

Figure 1 shows the temporal variations in 30-min mean and monthly mean values of sensible heat flux (H_s) and latent heat flux (LE) observed in the rice wetland during 2005. It should to be noted that the data missing periods in October and December were mainly due to instrument problem. Both H_s and LE values exhibited distinct seasonal changes. The 30-min mean H_s values were greatest in

[1] Spring means from March to May, summer from June to August, autumn from September to November, and winter from December to February

spring (> 300 W m^{-2}), and followed in autumn (> 100 W m^{-2}), whereas they were smaller in summer, with values of only a few tens of W m^{-2} (Fig. 1a). However, the seasonal change in *LE* values differed from that in H_s values. The *LE* values were greatest in summer (200 – 400 W m^{-2}), and remained high in autumn until November. The *LE* values increased obviously after soils were flooded in mid-March (Fig. 1b).

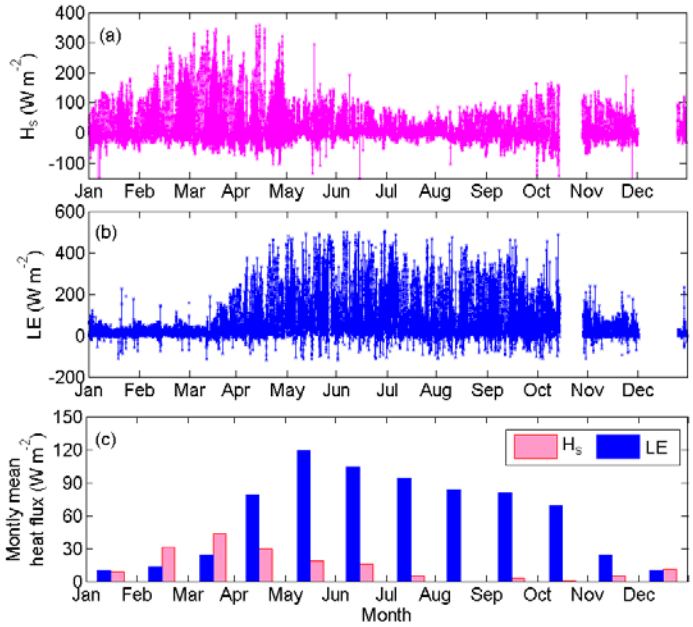

Fig. 1 Time series of 30-min mean (a) sensible heat flux (H_s) and (b) latent heat flux (*LE*), and (c) the monthly mean H_s and *LE* in the Panjin rice wetland during 2005.

The monthly mean H_s values reached a peak of 43.3 W m^{-2} in March and retained small values from July to November, whereas the monthly mean *LE* values reached a maximum of 118.7 W m^{-2} in May and then decreased slowly from May to October (Fig. 1c). Because the soils were flooded from April to November, the *LE* values were markedly higher than the H_s values due to strong evaporation at the surface, but the H_s values were slightly higher than the *LE* values in February and March when the surface was dry. Comparing with the seasonal variation of heat fluxes observed over a reed wetland in Panjin during 2006 [30], the monthly mean values of *LE* were relatively larger at the rice wetland than those observed in the reed wetland.

As shown in Fig. 2a, the 30-min mean CO_2 concentration values in 2005 were mostly between 300 and 500 ppm over the Panjin rice wetland. The background concentration of CO_2 during the winter (>400 ppm) was larger than that during the other seasons because of the coal-fired heating in the 2005 cold winter, but it dropped quickly after the heating stopped in early March. The atmospheric CO_2 concentration increased after seed broadcasting in mid-April through transplanting in mid-May, with an increase of 32 ppm due to the large amount of CO_2 generated by crop respiration. With increasing crop photosynthesis, the CO_2 concentration gradually decreased, with a minimum monthly mean value of 349 ppm reached in July (Fig. 2a). The F_c exhibited large negative values from mid-June to late September corresponding with the period of crop growth. The highest negative 30-min mean F_c value of approximately –2.0 mg CO_2 m^{-2} s^{-1} occurred during the summer, but during the winter, early spring, and late autumn, the 30-min mean F_c values were closer to zero. The highest negative monthly mean F_c value of –0.29 mg CO_2 m^{-2} s^{-1} occurred in July, and except for July, August, and September, the monthly mean F_c values were close to zero due largely to the state of vegetation at the surface (Fig. 2b).

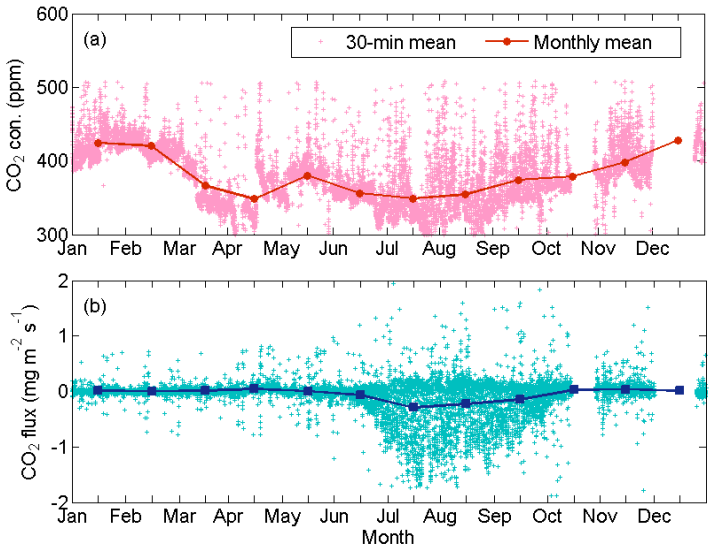

Fig. 2 Temporal variations in the 30-min and monthly mean (a) CO_2 concentration and (b) CO_2 flux (F_c) in the Panjin rice wetland during 2005.

Diurnal Variations in Heat and CO_2 Fluxes during Various Growth Stages and Months

The daily variations in heat and CO_2 fluxes and CO_2 concentration for three different growth stages of the rice crop were compared, including the early growth stage represented by 5–8 June, the middle growth stage represented by 17–20 July, and the late growth stage represented by 19–22 September (Fig. 3). The selected days were all clear days without apparent synoptic processes.

Both H_s and LE exhibited strong diurnal variation during the three growth stages, with peak values occurring at mid-day. The H_s values during the early and late growth stages were essentially equal, but were larger than those during the middle growth stage. The LE values during the middle and late growth stages were similar to each other but were smaller than those during the early growth stage (Fig. 3a, 3b).

The daily variation in F_c values was readily apparent during the middle and late growth stages. During the middle growth stage, F_c values exhibited peak negative values of –1.8 mg CO_2 m^{-2} s^{-1} at mid-day, which were approximately three times greater than those during the late growth stage, whereas the daily variation in F_c was weak during the early growth stage, with mid-day values of approximately –0.2 to 0.3 mg CO_2 m^{-2} s^{-1} (Fig. 3c). Feng et al. [19] reported that normalized difference vegetation index (NDVI) values retrieved from satellite images from 15 April to 19 August were highest in mid-July over the Panjin rice wetlands. The NDVI values were approximately 0.5 and 0.8 for the middle of June and July, respectively, which explains why the negative F_c values were greatest in July. The variation in CO_2 concentration corresponded with the changes in F_c, with the minimum values occurring at mid-day. The CO_2 concentration during the middle growth stage was much lower than that during other two stages because the photosynthetic activity of the crop absorbed a large amount of CO_2 (Fig. 3d).

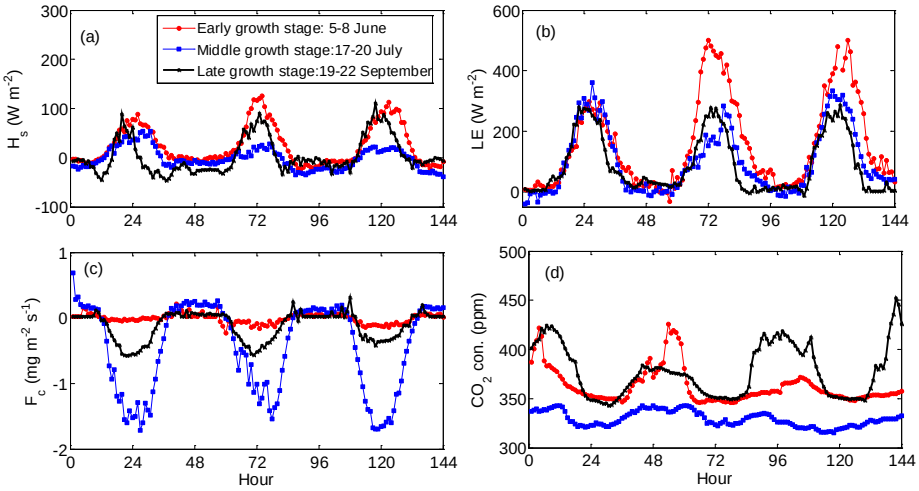

Fig. 3 Diurnal variations in (a) sensible heat flux, (b) latent heat flux, (c) CO_2 flux, and (d) CO_2 concentration in early growth stage (5-8 June), middle growth stage (17-20 July), and late growth stage (19-22 September) over the Panjin rice wetland during 2005.

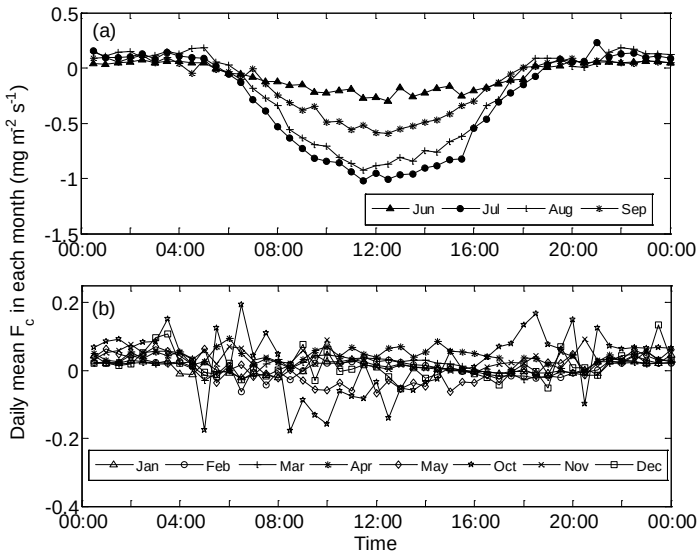

Fig. 4 Diurnal variations in CO_2 flux averaged in each month (a) during the main growing season (from June to September) and (b) during the remaining months in 2005 at the Panjin rice wetland.

Based on the seasonal variation in F_c shown in Fig. 2b, the main growing season for the Panjin rice wetland in 2005 was characterized by markedly negative F_c values during June through September. The daily variation in the F_c averaged for each month of 2005 is shown in Fig. 4. For the main growing season (Fig. 4a), the average F_c values exhibited a significant daily change, with the peak negative values occurring at 12:00 local time (LT). The peak negative F_c values during the daytime were greatest in July (–1.02 mg CO_2 m^{-2} s^{-1}) and were smaller, in rank order, in August (–0.93 mg CO_2 m^{-2} s^{-1}), September (–0.52 mg CO_2 m^{-2} s^{-1}), and June (–0.28 mg CO_2 m^{-2} s^{-1}). During the remaining months, the mean F_c values did not exhibit obvious daily variation, with mean and mean square root values for F_c being 0.02 and 0.04 mg m^{-2} s^{-1}, respectively (Fig. 4b); however, the daily variation in F_c values during May and October exhibited a relatively wider range, with larger negative values during the daytime and larger positive values at nighttime.

Monthly Variations in Cumulative CO_2 Fluxes and Comparison with Other Wetlands

The cumulative F_c values for each month were estimated by multiplying the monthly mean daily variation in F_c by the number of days in the same month. Missing F_c data, especially for October and December, were replaced with the mean daily F_c values, as shown in Fig. 5. The Panjin rice wetland

was a CO_2 source during most months, but not during the growing season. Rice wetlands absorbed the largest amount of CO_2 in July (–789.3 g CO_2 m^{-2} $month^{-1}$). The total F_c value during the entire year of 2005 was estimated to be –1570 g CO_2 m^{-2} $year^{-1}$, indicating that the rice wetland in Panjin acted as a large CO_2 sink. Feng et al. [19]estimated the total area of rice fields in Panjin to be 1649.3 km^2 based on an advanced land observing satellite (ALOS) image taken on 20 June 2006. Therefore, the amount of CO_2 absorbed by the Panjin rice wetlands in 2005 can be roughly estimated as 2.59×10^6 t CO_2 $year^{-1}$. The Panjin rice wetlands probably offset the effects of greenhouse gases on a certain degree and influence the local and even regional climate.

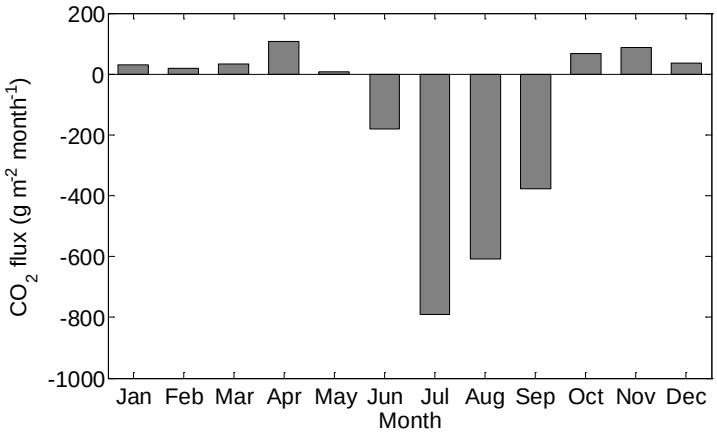

Fig. 5 Cumulative CO_2 flux in each month of 2005 at the Panjin rice wetland.

The total F_c values estimated by various researchers at various wetlands (rice and reed wetlands) in China are listed in Table 2. Based on the EC technique, Zhou et al. [32] estimated that the total F_c during 2005 at a reed wetland in Panjin was –1441 g CO_2 m^{-2} $year^{-1}$, a smaller negative value than the F_c value of –1570 g CO_2 m^{-2} $year^{-1}$ determined for the rice wetland in the present study. Using EC systems, Wang et al. [34] determined the net CO_2 uptake in the atmosphere at a rice paddy ecosystem in a subtropical region of China to be 1435 g CO_2 m^{-2} $year^{-1}$, which included CO_2 emissions of 617 g CO_2 m^{-2} $year^{-1}$ during the non-growing season, CO_2 uptake of 881 CO_2 g m^{-2} $year^{-1}$ during the early season (from 4 May to 18 July), and CO_2 uptake of 1171 g CO_2 m^{-2} $year^{-1}$ for the late season (from 19 July to 16 October). The difference between the prior results and those of this study are likely due to the different rice varieties used and the soil types in the southern and northern regions of China. Because the climate, location, and planting system used in Northeast China differ from those of south China, paddies in the former emitted less greenhouse gases than those in the latter [35]. Besides, for other rice paddies in various regions of East Asia, Saito et al. [12] measured a cumulative F_c value of 1246.7 g CO_2 m^{-2} from May to October 2002 in a rice paddy in central Japan using the EC method, showing that our results are similar to those in [12].

Table 2 Cumulative F_c measured in different rice paddies and other wetlands in China reported in different literatures.

Literatures	Observational site	Observational period	Observational Height	Total F_c (g CO_2 m^{-2})	Method
Xiao et al. [36]	Rice field, Shanghai, China	May-Oct	—	1361.5 (1 year)	Static Chamber
Wang et al. [34]	Rice wetland, Jiangsu, China	May 2008-Apr 2009	3 m	1435.0 (1 year)	EC technique
This study	Rice wetland, Liaohe Delta	Year of 2005	4.5 m	1570.0 (1 year)	EC technique
Zhou et al. [32]	Reed wetland, Liaohe Delta	Year of 2005	4.5 m	1441.0 (1 year)	EC technique
Li et al. [30]	Reed wetland, Liaohe Delta	Year of 2006	6.5 m	1290.0 (1 year)	EC technique
Han et al. [37]	Reed wetland, Yellow River Delta	May-Oct 2010	2.8 m	956.0 (6 months)	EC technique

Conclusions

Seasonal variations in heat and carbon dioxide fluxes in an artificial rice wetland in the Liaohe Delta of Northeast China during 2005 were investigated based on observational data obtained using the EC technique. The results indicated that the H_s was highest from February to April, which was the inverse of the variation in the *LE*. The maximum monthly mean H_s and *LE* values were 43.3 W m^{-2} in March and 118.7 W m^{-2} in May, respectively. The F_c values exhibited large negative values from mid-June to late September that corresponded to the periods of crop growth, with a maximum negative value of approximately –2.0 mg CO_2 m^{-2} s^{-1} during summer and small negative values during winter, early spring, and late autumn. The CO_2 concentration was between 300 and 500 ppm, and it varied in a manner similar to that of the F_c during the main growing season (June–September).

The heat and CO_2 fluxes exhibited marked daily variation during the three different growth stages of the crop. F_c values exhibited peak negative values at mid-day of approximately –0.6 mg CO_2 m^{-2} s^{-1} during the early growth stage (5–8 June), –1.8 mg CO_2 m^{-2} s^{-1} during the middle growth stage (17–20 July), and –0.2 to 0.3 mg CO_2 m^{-2} s^{-1} during the late growth stage (19–22 September). The H_s values during the early and late growth stages were essentially equal (>100 W m^{-2}), but were greater than that during the middle growth stage (~50 W m^{-2}), whereas *LE* values during the middle and late growth stages (>300 W m^{-2}) were similar but were less than that during the early growth stage (>500 W m^{-2}).

Based on the average daily variation in the F_c for each month of 2005, the total F_c for the entire year to be –1570 g CO_2 m^{-2} $year^{-1}$, with the largest negative F_c value of –789.3 g CO_2 m^{-2} $month^{-1}$ occurring during July. Comparison of these data with the total F_c values reported in previous studies for various rice wetlands and reed wetlands in China shows that most of the results were within the same order of magnitude, ranging from 1361.5–1570 g CO_2 m^{-2} $year^{-1}$. Our results showed that the rice wetlands in Panjin probably act as a large CO_2 sink.

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