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The Regulating Role of Meteorology in the Wetland-Air CO_2 Fluxes at the Largest Shallow Grass-Type Lake on the North China Plain

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Abstract: Lakes are hot spots of carbon cycles in inland aquatic systems. As a vital factor, meteorology, including air temperature, precipitation, wind speed and evapotranspiration, is profoundly affecting or even regulating the wetland-air CO_2 exchanges. Compared with some other similar lakes in China, the largest shallow grass-type Baiyangdian Lake (BYDL) acts as a vital CO_2 sink on the North China Plain. The purpose of this study is to reveal the effects of meteorology on the process of CO_2 flux variation. Based on the method of the eddy covariance, the daily average wetland-air CO_2 flux at the BYDL over the monitoring period from April 2019 to November 2020, reached -0.63 µmol m^{-2} s^{-1}, and the annual average reached -0.71 µmol m^{-2} s^{-1} from 12 April 2019 to 12 April 2020. The CO_2 sink fluxes varied with the seasons and reached the maximum in summer. Temperature and evapotranspiration are two major driving factors, whose higher values can positively improve the wetland CO_2 sinks. Precipitation generally coincides with the CO_2 sinks, but the relatively larger summertime precipitation (0.39 m in 2020, compared with that of 0.17 m in 2019) inhibits the CO_2 uptakes on longer timescales. A moderate wind speed in the range of 1.6~3.3 m s^{-1}, promoted the CO_2 sinks for the shallow grass-type lake. Compared with previous studies at the same or similar wetlands, consistent CO_2 sink fluxes are found. Further in this study, the variation trends of CO_2 sinks with the changing meteorological factors are revealed for the first time in this type of wetland. Once meteorology is determined under both the anthropogenic and climatic impacts, the evaluation and prediction of the lacustrine carbon cycling could be more precise. Generally, this study will serve as an important data point into the global understanding of lake carbon fluxes.

Keywords: wetland-air interface; CO_2 flux; meteorology; eddy covariance; temperature; evapotranspiration; carbon sink; shallow lake; reeds

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1. Introduction

Lakes are significant regulators in the terrestrial carbon cycle, which act as either sources or sinks of CO_2 [1,2]. Dissolved CO_2 concentrations in inland waters are usually supersaturated relative to the atmosphere. This leads to most inland lakes to be characterized by high CO_2 emissions [3,4]. However, eutrophic lakes are generally undersaturated for CO_2 and tend to be a sink for the atmospheric CO_2, due to their high primary production [5,6]. In highly populated plains with a high intensity of industrial and agricultural activity, the anthropogenic pollution (including large amounts of nutrients) inputs and the manual water volume regulation deeply alter the hydrochemical equilibrium and the carbon cycles in lakes.

The Baiyangdian Lake (BYDL) is the largest shallow grass-type freshwater lake on the North China Plain (NCP), where both eutrophication and artificial water diversion are ongoing. Nevertheless, as the core water environment of the Xiongan New Area, it is a hot spot for regulating the regional CO_2 cycle. Previous studies on the wetland-air CO_2 flux at the BYDL found that the reed vegetation was abundant, and the sedimentation rate was much greater than that of other lakes, which was overall, a strong CO_2 sink area [7]. During the growing season, from June to October, the CO_2 absorption by the BYDL ecosystem was greater than its release. The nighttime CO_2 release rate was <2.33 g C m^{-2} d^{-1}, and the daytime CO_2 absorption rate can be as high as 7.84 g C m-2 d-1, leading to a net absorption rate of 4.90 g C m^{-2} d^{-1} [8]. Niu et al. [9] measured the CO_2 release rate at the BYDL littoral zones from March to November and found them to be 0.12~3.49 g C m^{-2} d^{-1}, using the closed static chamber method. Zhao and Wang [10] used static chamber-gas chromatography to obtain the CO_2 release fluxes from different wetland sub-zones in the BYDL, from May to October, which were consistent with the above results. They pointed out that areas with reeds exhibited lower CO_2 release fluxes than those without plants. The previous results show that the CO_2 release rate of the BYDL is much lower than the CO_2 absorption rate, indicating a net CO_2 sink area. Compared with other inland wetlands in China, the BYDL functions as an outstanding carbon sink [8].

In such a typical carbon sink lake with intensive human activities, how local meteorological factors regulate the wetland-air CO_2 fluxes is still unclear. Especially, the connections between the meteorological elements and the wetland-air CO_2 fluxes, urgently need to be revealed, in order to obtain the more precise predictive evaluation for the regional lacustrine carbon sinks. We hypothesize that meteorology plays a regulating role in the wetland-air CO_2 exchanges. To clarify the regulating influence, we quantify the air temperature, precipitation, wind speed, evapotranspiration, and wetland-air CO_2 fluxes over 18 months, during 2019~2020. In addition, we analyze the correlation between the above terms. We build on the literature by (1) applying the eddy covariance method to reveal the controlling effects of meteorology on the wetland-air CO_2 fluxes; and (2) by assessing the level of the CO_2 sinks at the shallow grass-type lake, and comparing with other lake-wetland systems.

2. Methods

2.1. Study Site

The Baiyangdian Lake (BYDL), known as the "Pearl of North China" is located in Xiongan New Area, Hebei province (Figure 1). It was the largest shallow freshwater eutrophic wetland in the NCP, bounded by embankments with a maximum area of about 366 km^2. Without significant inlets or outlets in the system, the wetland was under very weak flow conditions. Aquatic plants are widely inner-distributed, with the reed growing area of 94 km^2, accounting for 54.6% of the total wetland area [11]. Their growing season mainly covers from May to October. The study site is in a temperate continental monsoon climate, with an arid and windy spring, a hot and rainy summer, a cool and refreshing autumn, and a cold and dry winter. The average annual temperature is 12.1 °C, and the average precipitation is about 500 mm a^{-1}, with 80% concentrated in June to September. The multi-year average potential and the actual evapotranspiration at the BYDL basin are 1031.1 mm and 461.1 mm, respectively [12]. The study site is located in the north of the BYDL, where the reeds are widely distributed except for in the limited waterways. The annual water level variation is within 1 m (Figure 2), with a small flooded area change around the tower, during the observation period. The measurements at this typical location can be highly representative for the whole wetland.

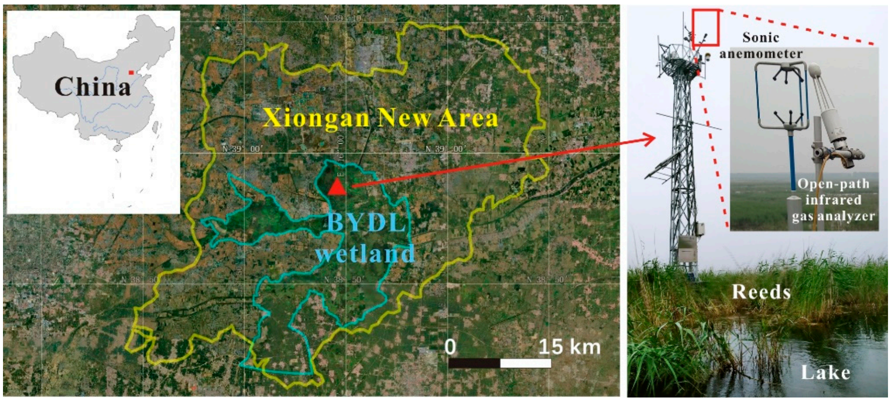

Figure 1. The location of the BYDL and the LI-COR 7500 eddy covariance analysis system for monitoring the meteorology and the wetland-air CO_2 exchange fluxes.

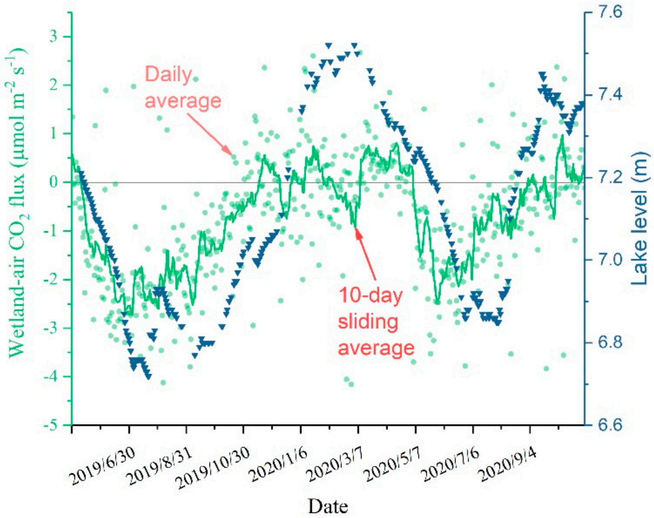

Figure 2. Ten-day sliding average CO_2 flux and daily lake water level during the monitoring period.

2.2. In-Situ Monitoring of the Meteorological Data

The in-situ measurement, tower, and site design considerations followed Aubinet et al. [13] and Burba [14]. In 2019, a concrete platform was built in the Shaochedian Lake (the largest sub-lake in the north of the BYDL), with a distance of 1.5 km from the lakeshore. The LI-COR 7500 eddy covariance analysis system (Licor Inc., Lincoln, NE, USA) was set up on this platform, with a height of 10 m. The system includes a three-dimensional ultrasonic anemometer (Gill sensor, Lymington, UK), air temperature and pressure sensors, open-path infrared gas analyzer (LI-7500 DS), and rain gauges (Figure 1). The CO_2 flux on the lake surface (the positive value indicates the upward release, and the negative value is the downward absorption), and the meteorological data, including evapotranspiration, air temperature, wind direction/speed (u, v, w), and precipitation can be real-time monitored and transmitted online. The monitoring period started on12 April 2019 until 18 November 2020, covering a total of 586 days, and the actual number of days for obtaining the complete data was 574 days. All of the output data are averaged by half an hour, with a sampling frequency of 10 Hz and a fetch area of 1 km around the tower. The wetland surface cover under the tower was almost homogeneous, based on the investigation and the satellite image around the tower.

2.3. Eddy Covariance Approach

The daily evapotranspiration rates and the CO_2 fluxes at the lake-air interface can be obtained directly from the eddy covariance daily data. The daily total evapotranspiration/CO_2 fluxes can be best described as a function of the product of the vertical wind speed and vapor pressure/CO_2 concentration difference between the water surface and atmosphere. The vertical flux of the water vapor (F_{ET}) and CO_2 (F_c), can be written as [15]:

$$F_{ET} = (1 + \mu\sigma)\left[\overline{w'\rho_v'} + (\overline{\rho_v}/\overline{T})\overline{w'T'}\right] \quad (1)$$

$$F_c = \overline{w\rho_c} = \overline{w'\rho_c'} + \overline{w}\,\overline{\rho_c} \approx \overline{w'\rho_c'} \quad (2)$$

where $\mu = m_a/m_v$ and $\sigma = \rho_v/\rho_a$; m_a and m_v are the molecular masses ('weight') of dry air and water vapor constituents, respectively; ρ_v and ρ_a are the density of the water vapor and the dry air constituents, respectively; w is the vertical velocity of the dry air constituent; T is the absolute temperature; ρ_c is the density of CO_2 in the air. Covariances were calculated by first filtering the spikes of the 10 Hz sampled data and then using a 30 min block average. The coordinate frame was rotated using the planar-fit method [16] frequency domain corrections for the path length averaging and the sensor separation were applied [17], and the density fluctuations were accounted for in the calculation of the fluxes. The sonic temperature was used to calculate the sensible heat flux using the method suggested by Paw U et al. [18] which accounts for a missing energy balance term associated with the expansion of air during evaporation under a constant pressure. The fluxes were measured when the wind was blowing from the direction within ±5° of the back of the anemometer. Approximately 2% of the data were omitted due to possible interference from the anemometer support and the IRGA mounted behind the anemometer.

2.4. Data Process and Correlation Analysis

Due to the meteorological influences, instruments and human disturbance, etc., the daily evapotranspiration sequence obtained by the field monitoring often loses data or exist gaps. In order to eliminate the impact of the data volatility of the time series, multiscale moving averages can reveal the characteristics of the land surface's physical or physiological processes inherent in different cycles of the sequence, while inhibiting the randomness of the features [19]. The original data lost 456 items, leading to a deletion rate of 1.62%. When obtaining the dynamic curves of the meteorological elements, including the CO_2 flux, a 10-day sliding average after excluding the spikes is performed to eliminate the sudden change of the special cases or the data loss (Figure 2). The smooth and continuous sliding average curve can clearly reflect the temporal variation trend. The quality control and data filtering also followed Morin et al. [20].

However, when analyzing the meteorological characteristics on a monthly or seasonal scale, the daily mean after the elimination of the spike is directly used, to exclude the staggered time from the sliding average approach. With the help of SPSS statistics software (IBM®), the correlation analyses were conducted between the meteorological factors and the wetland-air CO_2 exchange fluxes.

Last but not least, it should be clarified here that though the emission or absorption of CO_2 by an ecosystem is basically related to its interior physiological processes, the meteorological factors are focused in this paper to reveal the meteorological influencing trends on the wetland-air CO_2 fluxes. It is defined as the total CO_2 flux through the interface between the wetland, not only the water, and air. Thus, plant (i.e., reeds shown in Figure 1) photosynthesis and its fundamental factor of the solar radiation are not analyzed or emphasized.

3. Results

3.1. Meteorological Conditions

The Baiyangdian Lake (BYDL) is located in a typical temperate semi-arid monsoon climate. From the 10-day sliding average monitoring data of the temperature, precipitation, wind speed, and evapotranspiration (Figure 3A), it can be seen that during the monitoring period, the rain and heat were concentrated in the same period, mainly in summer (Figure 3B,C and Figure 4E). Wind speed is greater in spring than in other seasons, which decreases with the temperature rising and falling (Figures 3D and 4C). Daily evapotranspiration is positively correlated with the daily average temperature and wind speed (Figure 4A,B). The relatively heavier precipitation corresponds to a wind speed range of 1.9~3.4 m s^{-1}, with a lighter precipitation under either faster or slower wind speeds (Figure 4D). For the two gray bands in Figure 4D,E, it is shown that the relatively high precipitation occurred on relatively hot days (temperature range of 23~28 °C) and light breezes (wind speed range of 1.9~3.3 m s^{-1}). At a smaller precipitation, the daily evapotranspiration rate fluctuates in a large range. As the rainfall increases (>80 mm), the evapotranspiration tends to converge to the annual average (4.39 mm d^{-1}, Figure 4F). Dividing the four seasons by month (winter: December to February, spring: March to May, summer: June to August, autumn: September to November), the seasonal variations of the above four meteorological elements are characterized (Figure 3B–E). The temperature, precipitation, and evapotranspiration show a good consistency of summer > spring > autumn > winter, while the wind speed is different, with a variation trend of spring > summer > autumn > winter.

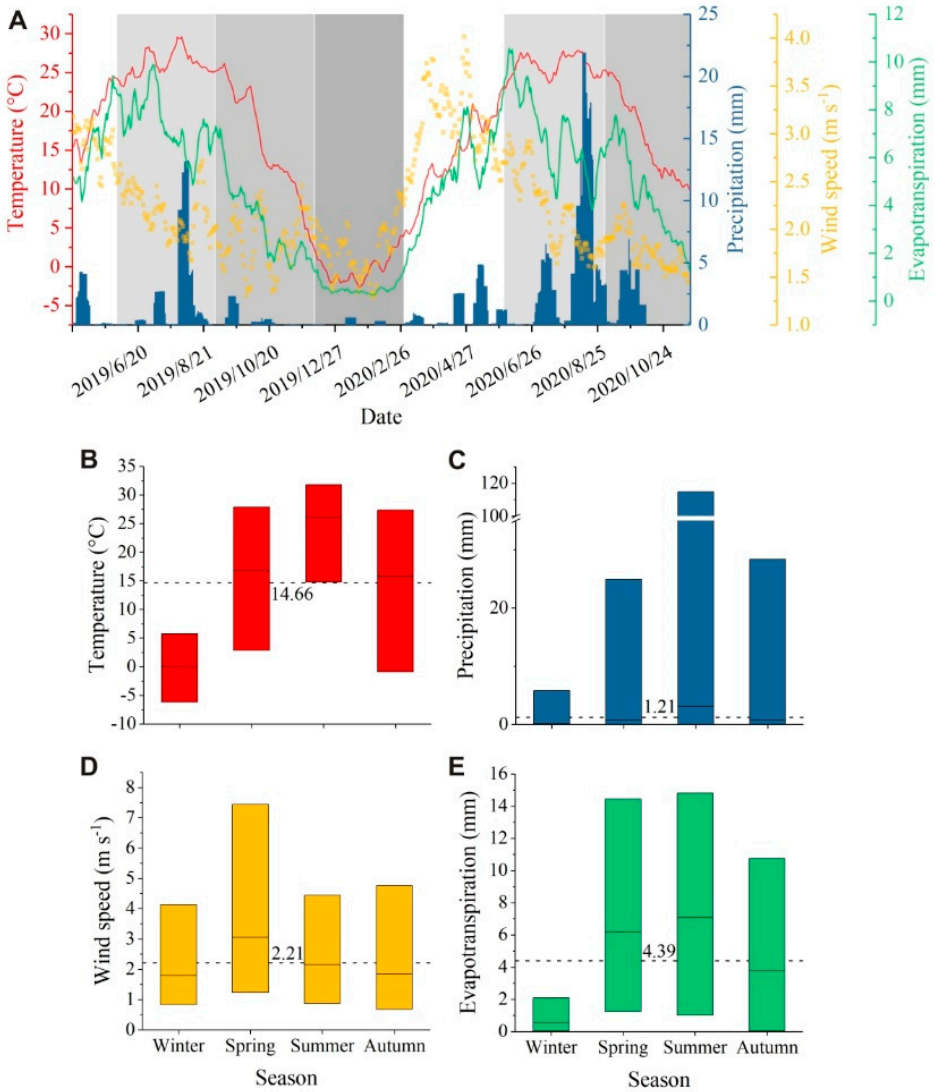

Figure 3. (**A**) Meteorological conditions, and its seasonal ranges for (**B**) the air temperature, (**C**) precipitation, (**D**) wind speed, and (**E**) evapotranspiration. The bar colors in (**B**–**E**) correspond to those in (**A**), the black line in each bar indicates the seasonal average value, and the dotted line across the bars denotes the average value during the monitoring period.

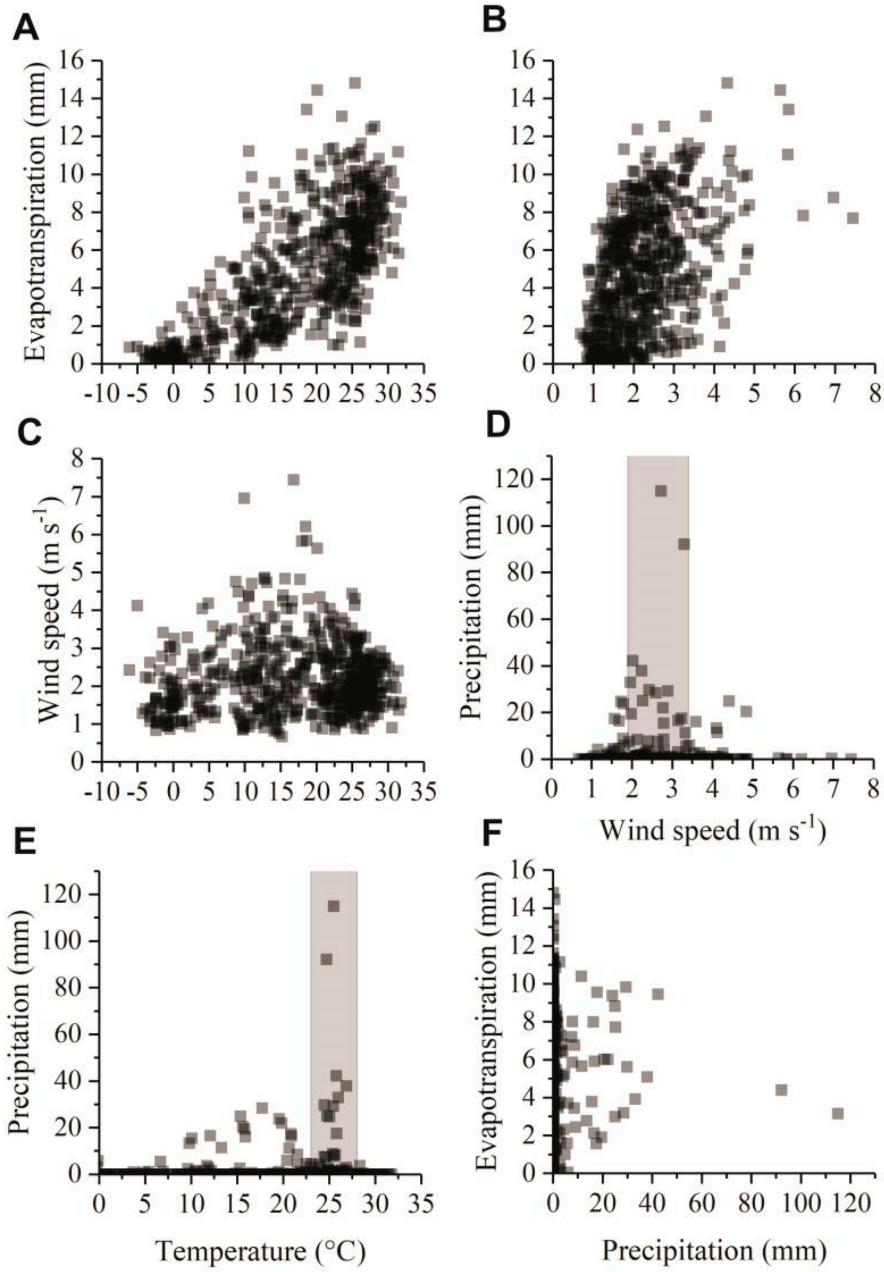

Figure 4. Relationships between every two meteorological factors of the daily timescale: (**A**) evapotranspiration and temperature, (**B**) evapotranspiration and wind speed, (**C**) wind speed and temperature, (**D**) precipitation and wind speed, (**E**) precipitation and temperature, (**F**) evapotranspiration and precipitation. The shaded parts on Figure 4D, E indicate the wind speed or temperature range corresponding to relatively higher precipitation.

3.2. *Temporal Variations of the Wetland-Air CO_2 Exchange Fluxes*

Based on the monitored data from the LI-COR 7500 eddy covariance system, it was found that the BYDL is a net CO_2 sink area overall, with a monitoring period averaged absorption rate of −0.63 μmol CO_2 m^{-2} s^{-1} (Figure 2). The monthly and seasonal average wetland-air CO_2 exchange fluxes present regular temporal fluctuations (Figure 5A). From May to September, it acts as a net sink of CO_2, especially in the summer when the reeds grow vigorously, while the remaining months, from October to April, show a weak source and sink switches. The seasonal average wetland-air CO_2 net fluxes (unit in μmol m^{-2} s^{-1}, Figure 5B) decrease in the order of summer (−1.57) > autumn (−0.40) ≈ spring (−0.36) > winter (−0.10).

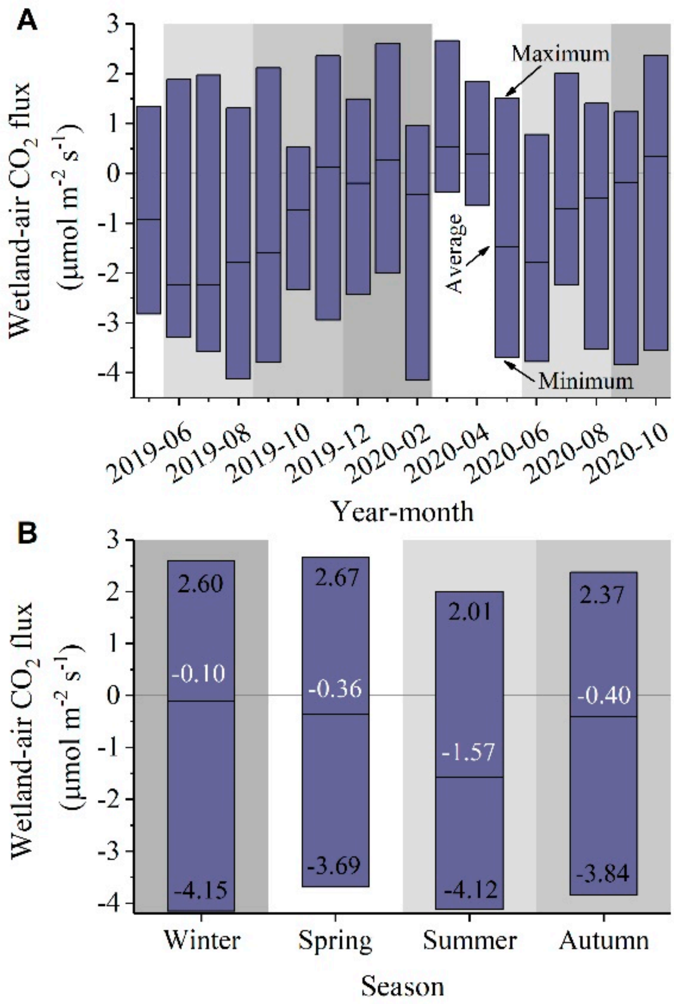

Figure 5. (**A**) Monthly average and (**B**) seasonal statistics of the daily wetland-air CO_2 exchange fluxes, the level of shading indicates the different seasons: from light to dark represents spring, summer, autumn, and winter.

3.3. Relations between the Wetland-Air CO_2 Fluxes and the Meteorological Variables

The wetland-air CO_2 flux is affected by the meteorological elements in different ways. From Figure 6, the relationship between them is revealed: (1) For daily average air temperature (Figure 6A): the sources and sinks of CO_2 are basically balanced in spring and autumn (10~22 °C) and winter (<10 °C), while in summer (>22 °C), it behaves as a strong sink. (2) For the daily rainfall (Figure 6B): there is no obvious trend for the wetland-air CO_2 flux, as the precipitation is rising. Nevertheless, the CO_2 sinks are generally more common than the sources during the precipitation events, of varying intensities. (3) For the daily average wind speed (Figure 6C): the CO_2 absorption is slightly stronger than the release when the wind is light air (0.3~1.5 m s^{-1}) or a gentle breeze (3.4~5.4 m s^{-1}), while the sinks are obviously more than the sources, when the wind is a light breeze (1.6~3.3 m s^{-1}). The CO_2 releases tend to be dominant when the wind is at a moderate breeze (5.5~7.9 m s^{-1}). (4) There is a general negative correlation between the wetland-air CO_2 flux with the daily evapotranspiration (Figure 6D). When the evapotranspiration is relatively weak (<5 mm), the sources and sinks of CO_2 are basically balanced. When the evapotranspiration is moderate (5~10 mm), the absorption is significantly larger than its release. When the evapotranspiration is strong (>10 mm), they are overwhelming CO_2 sinks.

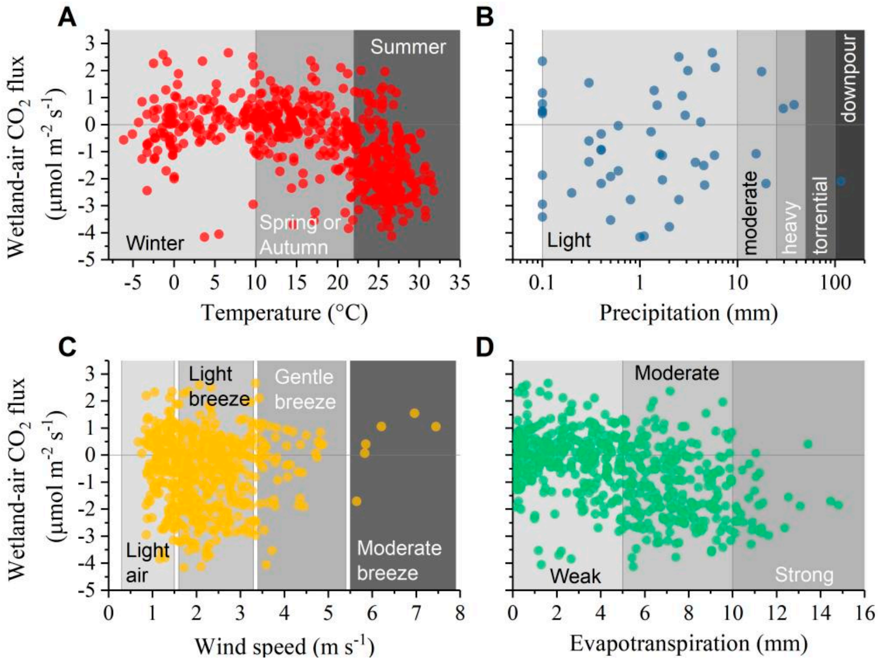

Figure 6. Relations between the daily wetland-air CO_2 fluxes and the four meteorological variables of (**A**) temperature, (**B**) precipitation, (**C**) wind speed, and (**D**) evapotranspiration; As the gray band darkens, the level of the corresponding meteorological factors increases. Note: the intervals of the meteorological variables comply with the related national standards in China.

Further, Pearson correlation analyses (Table 1) obtain results consistent with Section 3.1. There is a good positive correlation between the temperature and precipitation, and between the precipitation and wind speed ($p < 0.05$). Evapotranspiration is significantly positively correlated with the air temperature and wind speed ($p < 0.01$, Figure 4A,B). The wetland-air CO_2 fluxes are significantly inversely correlated with the temperature and evapotranspiration ($p < 0.01$), which can also be obtained from Figure 6A,D.

Table 1. Correlation coefficients between the wetland-air CO_2 fluxes and the meteorological factors.

	Temperature	**Precipitation**	**Wind Speed**	**Evapotranspiration**	**Wetland-Air CO_2 Flux**
Temperature	1				
Precipitation	0.099 *	1			
Wind speed	0.062	0.093 *	1		
Evapotranspiration	0.732 **	0.025	0.468 **	1	
Wetland-air CO_2 flux	−0.485 **	−0.012	0.051	−0.406 **	1

Note: * and ** indicate the significant correlation at the 0.05 and 0.01 level, respectively.

4. Discussion

4.1. The Role of Meteorology in the Wetland-Air CO_2 Exchanges

From Section 3.3, we can see that the relatively higher temperature (>22 °C, summer), moderate wind speed (1.6~3.3 m s^{-1}, light breeze) and stronger evapotranspiration (>5 mm d^{-1}, especially >10 mm d^{-1}) will jointly promote the wetland CO_2 absorption. For different level precipitations, from light to downpour, it is generally, but not obviously, beneficial for the wetland CO_2 absorption. The monitoring period covered two whole summers, in which seasons the CO_2 exchange rates are much higher than in the other seasons. By comparing the daily average CO_2 flux at the wetland-air interface during the two summers (Table 2), it was found the flux of 2019 was twice as high as that of the 2020. The temperatures, wind speeds, and evapotranspiration are close to each other in both summers, but the precipitation of the former is less than 50% of that of the latter. It is likely that the heavier precipitation generally corresponds to weaker light conditions. On the one hand, this hinders the stomata opening of the reeds and reduces the evapotranspiration or CO_2 absorption. On the other hand, the respiration can be enhanced, inhibiting the foliar absorption of CO_2. On the daily scale, precipitation is beneficial to the carbon sink of the reed wetlands, however, on a longer time scale of the quarter, more precipitation reduces evapotranspiration to a certain extent, and obviously weakens the carbon sink effect.

Table 2. Daily average meteorology and wetland-air CO_2 flux at the Baiyangdian Lake (BYDL) in the summers of 2019 and 2020.

Summer of the Year	Daily Average Temperature (°C)	Daily Average Precipitation (mm)	Daily Average Wind Speed (m s^{-1})	Daily Evapotranspiration (mm)	Daily Wetland-Air CO_2 Flux (μmol m^{-2} s^{-1})
2019	26.22	1.94	2.16	7.32	−2.10
2020	25.94	4.26	2.15	6.84	−1.03
Ratio of 2019 to 2020	1.01	0.46	1.01	1.07	2.03

4.2. Comparisons of the Wetland-Air CO_2 Fluxes with Previous Studies

The CO_2 absorption or release intensity varies in the different lakes, and the flux direction may be reversed. Even in the same lake, the CO_2 fluxes in different lake areas or seasons may be reversed. The values for the global lakes range from −0.17~0.54 μmol m^{-2} s^{-1} with a mean of 0.18 μmol m^{-2} s^{-1} (Table 3 in [4]). The CO_2 absorption flux at the BYDL is compared with those of other lakes with CO_2 sinks (Table 3). It was found that the BYDL has a relatively higher CO_2 sink capacity on the annual scale. The CO_2 sink fluxes (−2.24~0.34 μmol m^{-2} s^{-1}) from June to October are comparable to that (−2.34~−0.33 μmol m^{-2} s^{-1}) from a previous study at the BYDL [8]. This CO_2 absorption flux of −1.57 μmol m^{-2} s^{-1} in summer, is on the same order of magnitude as that of −2.75~−3.04 μmol m^{-2} s^{-1} in the Panjin reed wetland in the growing season (June–September, [21]). On the seasonal or annual average levels, the CO_2 absorption flux at the BYDL is higher than or close to those at other similar lakes, as shown in Table 3. For the seasonal variations of the different lakes, the summers show a stronger absorption or weaker releases of CO_2 than the winters ([22] and this study).

Table 3. Comparison of the wetland-air CO_2 absorption fluxes between the BYDL and other similar lakes.

Site	Wetland-Air CO_2 Flux (μmol m^{-2} s^{-1})	Reference
Dongtinghu Lake	−0.04 (daily average)	[23]
Chaohu Lake	−0.10 (daily average)	
Hongzehu Lake	−0.17 (daily average)	
Erhai Lake	−0.01 (daily average)	
Dianchi Lake	−0.12 (daily average)	
Donghu Lake	0.37 ± 0.29 (winter), −0.02 ± 0.06 (spring) −0.04 ± 0.11 (summer), 0.04 ± 0.09 (autumn)	[22]
Lake Daming	−0.10~0.04 (summer)	[24]
Taihu Lake	−2.23~0.19 (annual average: −0.73)	[25] (Monthly statistics)
Lake Batur	−0.03	[26]
Ngoring Lake	−0.70~−0.13 (June to September)	[27]
Yindeer Lake	−0.84~0.24 (annual average: −0.26)	[28]
Panjin reed wetland	−2.75 (June~September 2004) −3.04(June~September 2005)	[21]
Qinghai Lake	−0.84 ± 0.37 (Ice-covered) −0.40 ± 0.34 (Ice-free)	[29]
BYDL	−2.34~−0.33 (average: −1.29, June~October)	[8]

Table 3. *Cont.*

Site	Wetland-Air CO_2 Flux (μmol m^{-2} s^{-1})	Reference
BYDL	−2.24~−0.74 (average: −1.72, June~October 2019) −1.79~0.34 (average: −0.57, June~October 2020)	This study (Monthly statistics)
BYDL	−0.10 (winter), −0.36 (spring) −1.57 (summer), −0.40 (autumn) −0.63 (average over the monitoring period) −0.71 (annual average, from 12 April 2019 to 12 April 2020)	This study (Seasonal statistics)

4.3. Limitations of the Current Study

In this study, the meteorological elements are mainly analyzed to reveal the relations between them and the wetland-air CO_2 fluxes at the largest shallow grass-type lake. Actually, some other factors, including eutrophication [30], the hydrological situation [31], the spatial distribution [32], the global climate change [33], the biogeochemical function, etc., can also influence the wetland-air CO_2 fluxes. Eutrophication causes clear lakes to become a strong CO_2 sink, whereas humus lakes become a stable CO_2 source after the addition of external nutrients [34]. Hard-water lakes in central North America gradually changed from CO_2 sources to sinks with an increase in the annual mean pH value [35]. Previous monitoring data indicate that the water of the Baiyangdian Lake is alkaline and eutrophicated, which may be other reasons for its carbon sinks. Thus, further wetland CO_2 flux evaluations and regulations should consider the more complicated multi-parameter interactional ecosystem networks. Under the dual effects of global climate change (e.g., the temperature increase may enhance carbon sinks) and the artificial water diversion, which can change the lacustrine chemical environment and may promote carbon releases, it is necessary to further observe and judge how the meteorology and CO_2 flux at the BYDL will change and be controlled.

5. Conclusions

This study clarified the temporal variation of the CO_2 flux at the wetland-air interface at one typical site of the Baiyangdian Lake (BYDL), and its relationship with four main meteorological factors, including the air temperature, precipitation, wind speed, and evapotranspiration. Based on the eddy covariance method and the correlation analysis, the temporal variations of the CO_2 flux at the largest shallow grass-type lake on the North China Plain and its response laws to the local meteorological factors are revealed. Among the meteorological factors, temperature and evapotranspiration were significantly correlated with the wetland-air CO_2 fluxes. The relatively higher temperature (in summer) and stronger evapotranspiration contributed to a greater CO_2 absorption than in other seasons. However, the too slow or fast wind speeds will not help the wetland CO_2 sinks. Precipitation basically corresponds to the carbon sinks, while on an annual scale, more rainfall will hinder the CO_2 sink by decreasing evapotranspiration and increasing respiration. These findings are of scientific significance for the lacustrine eco-environmental evaluation and the carbon sink evolution trend analysis. In order to more comprehensively depict the CO_2 flux at the wetland-air interface in lakes under an anthropogenic effect and global climate change, further studies relating to the more complex physical or biogeochemical processes need to be taken into account.

Author Contributions: G.L., H.L. (Haitao Li), and H.L. (Hailong Li) designed this study. Q.W. and Y.Z. helped performing the data analysis. G.L. wrote the paper, and K.X. helped edit the language. All authors have read and agreed to the published version of the manuscript.

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