Analysis of the microclimate and CO₂ flux characteristics in arid desert wetland ecosystem in summer: A case study in Xihu desert wetland, Dunhuang, China

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Xihu desert wetland is an important and unusual environment in China or even in the world. However, until now, little research has been focused on the microclimate and CO₂ flux characteristics in this area. This paper reports the characteristics of daily variations of microclimate and CO₂ flux in the Dunhuang Xihu desert wetland, based on data observed in the desert wetland during a period of continuous fine weather in summer 2012. Results indicate that the characteristics of the micrometeorology were significantly affected by the land–lake breeze during the study period, and updrafts were prevalent in this region. The friction wind speed and the vertical velocity were much greater than those in the Maqu grasslands. The energy budget was strongly imbalanced: the latent heat flux was significantly higher than the sensible flux. The daily mean values of total solar radiation and net radiation were larger than those in Maqu grasslands and Jinta oasis. There was a temperature inversion and inverse humidity gradient in the atmospheric surface layer at night. The desert wetland ecosystem was a carbon sink during the whole of the observation period, and the maximum rate of carbon absorption usually occurred at about 11:00 hr each day in this region.

1. Introduction

Arid and semi-arid regions cover more than one-third of the Earth's surface, making these systems the largest biome type in the world (Schlesinger 1991; Reynolds 2001). As a large part of the global terrestrial ecosystem, arid and semi-arid regions make a significant contribution to global climate change. Research has shown that the most significant contributions to the global increase in land surface temperature over the past century come from arid and semi-arid regions, which account

for 44% of the global land surface air temperature trend (Huang *et al.* 2012). In addition, the total organic carbon pool in soils in these regions accounts for approximately 15% of all global soil organic carbon (Schlesinger 1991; Lal 2004), and net primary productivity (NPP) of the drylands is estimated to comprise approximately 20% of total terrestrial NPP (Whittaker 1975).

In these regions, annual potential evaporation exceeds annual precipitation. Such regions are characterized by dry climates, high temperatures, strong light, low vegetation cover, low

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nutrition content, and low soil capacity for water conservation (Zhai and Zhang 2004), making ecosystems in these areas particularly vulnerable to environmental constraints. Research has indicated that increases in temperature and shifting precipitation patterns associated with climate change will result in changes in the structure (e.g., vegetation composition) and functions (e.g., carbon assimilation) of many arid ecosystems (Midgley et al. 2004). In addition, the spatial coverage of arid lands may increase dramatically as a result of climate change (Maestre and Cortina 2004). Considering the already large extent of arid and semi-arid ecosystems, an increase or decrease in area may have a significant effect on the global carbon balance and on climate change (Hastings et al. 2005).

Observational experiments provide the most direct means of obtaining data, and are the foundation for research in climate change in arid and semi-arid regions. Observational studies of plant communities, microclimates, and the ecological environment in arid regions can reveal ecological and environmental conditions, and changes in the environmental factors affecting the ecological environment (Zhang 2000; Zhang et al. 2004). Such studies can also provide insights into the ecological function of arid plant communities, and help with estimating their environmental benefits. The Xihu desert wetland is a national nature reserve located at the western end of the Hexi corridor of Gansu Province, approximately 120 km from Dunhuang city. It borders the Kumtagh Desert to the west, Aksai Kazakh autonomous county to the south, and Xinjiang Uygur Autonomous Region to the north. It has a typical desert ecosystem, while also being one of the most typical wetlands of the arid regions, making it an important and unique area for study. This area can be seen as a natural laboratory for research in desert-wetland ecosystems (Zheng et al. 2010). However, until now, there has been very little research carried out on the microclimate and CO₂ flux characteristics of this area.

In this paper, we present observations of daily variations in micrometeorological variables, ground surface radiation balance, ground surface energy balance and closure ratio, as well as daily CO₂ flux and density measurements collected in the Xihu desert wetland, Dunhuang during a period of continuous fine weather from August 21 to September 30, 2012.

2. Field site and methods

2.1 Field site

The study was conducted in the Xihu desert wetland National Nature Reserve, Dunhuang (92°45′–

93°50′E; 39°45′–40°36′N), which covers an area of 66 million hm². The northern part of the area is low-lying, while the southern part is more elevated, and the central area is an alluvial plain (figure 1). The area is surrounded by deserts and Gobi, and is classified as having a typical temperate continental climate. Here the natural vegetation is dominated by *Phragmites australis*, *Tamarix ramosissima*, and *Populus euphratica*, and the main associated species are *Lycium ruthenicum*, *Alhagi sparsifolia*, and *Glycyrrhiza inflata* (Chen et al. 2012). According to meteorological records from the Xihu Weather Station, the mean annual temperature is 9.9°C, with minimum and maximum mean daily temperatures of −30°C and 40°C, respectively. Mean annual precipitation is 39.9 mm, mean annual evaporation capacity is 2486 mm, and the drought index is greater than 16. The average wind velocity is 2.2 m·s^{−1}, and the mean annual number of days with gales is 15.4 d. There are 3115–3246.7 annual hours of sunshine, and the sunshine rate is 70%–73%. The total annual radiation flux is 641.8 kJ·cm^{−2} (Qi et al. 2010; Chen et al. 2012). The exact latitude and longitude of the observation point, which is surrounded by flat, open terrain, is 40°20′16.4″N, 93°44′6.4″E, and the elevation is 998 m.

2.2 Method

We made measurements of eddy covariance and of microclimate. Open-path flux sensors were mounted 3 m above the soil surface, above *Phragmites australis* standing approximately 1 m tall, and *Alhagi sparsifolia* which was approximately 0.4 m tall, and orientated in the direction of the prevailing winds. A three-dimensional sonic anemometer (CSAT3, Campbell Scientific, Logan, UT, USA) was used to measure fluctuations in wind speed, wind direction, and temperature. Water vapour and CO₂ concentrations were measured using an open-path infrared gas analyzer (LI-7500, LiCor, Lincoln, NE, USA). The Li-7500 was calibrated at regular intervals for CO₂ and water vapour using calibration gases and a dew point generator supported by the China Land-Atmosphere Coordinated Observation System, CLACOS. A data logger (CR3000, Campbell Scientific, Logan, UT) was used to record data at 10 Hz.

Air temperature (T_{air}) and humidity were measured at a height of 3 m on a tower (HMP45C, Vaisala Inc., Helsinki, Finland). A four-component net radiometer (Rn) (CNR-1, Kipp and Zonen, the Netherlands) was placed 3 m above the soil surface. Two self-calibrating soil heat flux sensors (HFP01) were placed 0.05 and 0.1 m below the soil surface. The soil temperature profile (109-L, Campbell Scientific Ltd., Edmonton, Alberta, Canada) and

Figure 1. Location of study area and observation point.

soil water content (SWC) profile (EnviroSMART, Campbell, Scientific Ltd., Edmonton, Alberta, Canada) were monitored adjacent to the micrometeorological tower. Soil temperatures were measured at five depths (0.1, 0.2, 0.4, 0.6, and 1.0 m). SWC was also measured at five depths (0.1, 0.2, 0.4, 0.6, and 1.0 m). Average soil temperature (TCAV) was determined at a depth of 0.2 m. Precipitation was collected and measured by a rain gauge (TE525MM, Texas Electronics Inc., Dallas, TX, USA).

The raw data were processed using the post-processing software Edire (University of Edinburgh, UK). Based on the recommendations of Lee *et al.* (2004), the following processing steps were applied: spike removal, auto-detection of the time delay between different sensors, conversion of the temperature measurement by the sonic anemometer into air temperature (Schotanus *et al.* 1983), tilt correction (Foken and Wichura 1996; Wilczak *et al.* 2001), and Webb–Pearman–Leuning correction (Webb *et al.* 1980). Internationally accepted interpolation methods were used to compensate for

missing data (Valentini *et al.* 2000; Falge *et al.* 2001; Gilmanov *et al.* 2007).

3. Results and discussion

3.1 Microclimate characteristics

The horizontal wind speed showed an obvious diurnal pattern in the Xihu desert wetland, Dunhuang, over the measurement period, for which there was continuous fine weather, and wind speeds were higher at night than in the daytime. The maximum horizontal wind speed occurred around midnight (figure 2a), which differs from the timing of maximum wind speeds at Maqu grassland (Ao *et al.* 2008) and Dunhuang oasis (Zhang and Zhou 2002), where the maximum occurs at dusk. Most vertical wind velocities were positive at the field site (figure 2a). The mean and maximum vertical wind velocities were 0.18 and 0.79 m·s⁻¹, respectively, which are significantly higher than those observed in Maqu grassland (Ao *et al.* 2008) and Dunhuang

Figure 2. The daily variations of micrometeorology factors over Xihu desert wetland. (a) Horizontal wind velocity (black line) and vertical wind velocity (red line), (b) friction wind velocity, (c) air temperature, (d) relative humidity of air, (e) soil temperature at different depths, and (f) relative soil moisture at different depths.

oasis (Zhang and Zhou 2002), and were associated with strong updrafts. Measurements of the friction wind velocity yielded the transportation and dispersion capacity in different spatial directions, and served as the turbulent velocity scale. Most friction wind velocities were greater than $0.1 \text{ m}\cdot\text{s}^{-1}$, and the maximum was $0.9 \text{ m}\cdot\text{s}^{-1}$ (figure 2b). This indicates a level of turbulent mixing in agreement with the observations, justifying their reliability. Figure 2(b) also shows that horizontal wind speeds were consistent with friction wind velocities, with the resulting fit demonstrating that the turbulent momentum flux was controlled by wind shear during the good weather conditions. This differs from a desert area (Hu *et al.* 1992) where turbulent momentum flux was generally controlled by the thermodynamic stability.

The minimum air temperature (T_{air}) in the surface layer occurred at around sunrise on each of the study days; the minimum value was 2.3°C , and the maximum occurring around sunset, was 36.2°C during the observation period (figure 2c). Figure 2(c) also shows the diurnal variation of air temperature in the surface layer which followed a trend of first increasing, and then decreasing, under similar net radiation conditions. This differs from observations at Maqu grassland (Ao *et al.* 2008), possibly as a result of locally varying circulation in the area. The relative humidity

of the air in the surface layer also showed a regular pattern during the observation period (figure 2d). Diurnal variation in the relative humidity of the surface layer depended on the strength of the underlying surface water vapour evaporation and turbulent exchange. The relative humidity of the air was low in the morning. After sunrise, rising temperatures facilitated evaporation and so the relative humidity of the air began to increase, peaking at noon. In the afternoon, the relative humidity of the air decreased gradually with the strengthening of vertical turbulent exchange, reaching a minimum at dusk. This trend in relative humidity in the Xihu desert wetland, Dunhuang differs from the general upward trend that was observed at Maqu grassland (Ao *et al.* 2008). The results presented here suggest the complexity of the microclimate in the study area.

Regular changes in soil temperature were observed at different depths (figure 2e). In layers at 0.1 and 0.2 m below the surface, the soil temperature varied sinusoidally. The peak soil temperature in the layer 0.2 m below the surface lagged behind that in the layer at 0.1 m, and both increased first and then decreased slowly with time during the observation period. The soil temperature in the layer 0.4 m below the surface did not vary sinusoidally. The explanation for the above phenomena is that the layers at 0.1 and 0.2 m below the surface

received more heat than the other deeper layers, because the Sun heated up the soil. This explains why the temperature in the upper two layers followed a more obvious sinusoidal pattern than that in the subsoils. Soil water content (SWC) also differed between the five soil depths. In the layer 0.1 m below the surface, SWC varied periodically and sinusoidally with time, but there was little change in SWC in the other layers, mainly because the Sun heated up the surface soil and increased the evaporation of soil water. However, in other soil layers, due to the weakness of solar heating at these depths, soil water evaporation was low, and the SWC was higher than that of the surface layer.

3.2 Characteristics of the ground surface radiation

Figure 3 shows the diurnal variations in several components of the ground surface radiation (figure 3a) and the albedo (figure 3b), which all exhibited significant regularity over the period of continuous fine weather at the study site.

The total solar radiation was the dominant term in the surface radiation balance, and was largely responsible for the observed variability in the other terms. The daily variation in total solar radiation (figure 3a) ranged from 0 to 1172.1 W·m⁻², and the maximum recorded solar radiation values on each day of the measurement campaign occurred at late afternoon. And the maximum values are slightly higher than that recorded at the Maqu grassland (Ao *et al.* 2008), and also about 100 W·m⁻² higher

than at Jinta Oasis (Zhang *et al.* 2005) for the same season. The total solar radiation amount varied with changes in solar altitudinal angle, air density, cloud fraction, and other parameters. There was an obvious diurnal variation, with higher solar radiation being recorded in the daytime and zero at night. Figure 3(a) shows the curve of total solar radiation to be smooth because of the depression of convective cloud in summer in this area. There was no super solar constant of the solar radiation (the total solar radiation is greater than the solar constant) during the observation period.

Reflected radiation (upward shortwave radiation) can be considered the result of a ‘mirror’ effect, whereby incoming solar radiation is reflected from the ground surface. As the site was largely covered by *Phragmites australis* and some other vegetation, it had a greater surface roughness and therefore lower reflectivity than Gobi and desert areas (Ji *et al.* 2003; Ma *et al.* 2012). Figure 3(a) shows that the reflected radiation was zero during the night; this was because there was no solar downward shortwave radiation at night. Figure 3(a) also shows that the amount of reflected radiation rose slowly after sunrise, reaching a maximum before or after noon. The diurnal variation in reflected radiation (upward shortwave radiation, figure 3a) ranged from 0 to 222.6 W·m⁻², and the maximum values of reflected radiation on each of the study days appeared shortly after midday each day.

The diurnal variation in atmospheric long-wave radiation at the field site was small (figure 3a),

Figure 3. The daily variations of (a) the ground surface radiation and (b) albedo over Xihu desert wetland of Dunhuang for a summer continuous fine weather.

varying from 289.6 to 463.9 W·m⁻², and was lower in the morning and higher in the evening. This diurnal fluctuation is larger than that observed in Maqu grassland (Ao *et al.* 2008) and in Jinta Oasis (Zhang *et al.* 2005). Atmospheric long-wave radiation is highly sensitive to moisture content, but is also affected by atmospheric density, moisture content, aerosol concentration, cloud, and some other factors. The altitude of the observation station was low and the humidity at this height was relatively high. Consequently, the measured atmospheric long-wave radiation was significantly higher than would be likely at higher altitudes.

The ground upward long-wave radiation can be represented as a mathematical formula:

$$F = \varepsilon \sigma T_g^4 \quad (1)$$

where ε is the emissivity, σ is the Stefan-Boltzmann constant and T_g is the land surface temperature. According to this formula, the measured variation in upward long-wave radiation is in agreement with the observed surface temperature change for this land surface cover. The surface temperature therefore determined the strength of the surface long-wave radiation. Figure 3(a) shows that the surface long-wave radiation in the Xihu desert wetland exhibits a regular diurnal variation, although the surface temperature was very high in this area during summer, and the diurnal temperature range was higher. It follows that since the surface temperature was lower at night, the surface long-wave radiation was also low in this area. From figure 3(a), it is evident that the surface long-wave radiation does follow an obvious diurnal pattern, varying from 317.0 to 587.7 W·m⁻². The surface upward long-wave radiation was relatively low in the early morning and higher in the late afternoon, and was likely to be higher at our measurement altitude than at higher altitudes. The observed daily total surface long-wave radiation in this area was also higher than that at other higher altitudes (Ao *et al.* 2008).

The diurnally integrated values of the total solar radiation, the reflected radiation, the atmospheric long-wave radiation, and the ground upward long-wave radiation were 27.3, 5.5, 33.2, and 38.3 MJ·m⁻²·d⁻¹, respectively. Thus it can be seen that the ground upward long-wave radiation played the most significant role in the radiation balance at the Xihu desert wetland, followed by atmospheric long-wave radiation, and the reflected radiation contributed the least.

The surface albedo is an important physical quantity in the study of land surface processes, since it is a measure of the land surface's capacity for reflecting solar radiation. Determining the surface albedo is significant to any understanding

of the thermodynamic properties of underlying surface, since the absorption of solar radiation by the atmosphere is weak, and the greatest energy input comes from the surface. Any change in surface albedo necessarily affects the surface energy balance and alters the bi-directional energy transfer between the land surface and the atmosphere, which ultimately affects the local atmospheric circulation. Xihu desert wetland is largely covered by *Phragmites australis* and some other vegetation. The surface albedo in this area has a regular diurnal variation. Figure 3(b) shows that the surface albedo follows a 'U' shape, with a minimum at midday, and a high in the morning that might be due to dew condensation. The mean surface albedo was 0.2 over the study days, which is higher than that measured for Maqu grassland (Ao *et al.* 2008).

3.3 Ground surface energy balance

Obvious periodic variations were observed in the net radiance, sensible heat flux, latent heat flux, and soil heat flux (figure 4a). All these increased after sunrise, reached their maxima after noon, and then gradually decreased. However, the phases of these variables were not consistent. Variations in latent heat flux followed those of the net radiation flux, and the peak appeared at early afternoon; the sensible heat flux and soil heat flux maxima occurred half an hour later than the net radiation flux. The net radiance flux (figure 4a) was positive 10–20 min before sunset in the daytime, but was negative 20–30 min before sunrise. It passed through zero twice during the day and varied from –61.9 to 830.3 W·m⁻². The net radiance flux in the daytime was considerably greater than that at night, because the ground continuously transmitted long-wave radiation to the atmosphere at night-time. It is also a consequence of the fact that the land surface of Xihu desert wetland is a strong heat source in the daytime and becomes a weak cold source in the evening. There were some negative sensible and latent heat fluxes measured at night-time in this area (figure 4a). These probably resulted from an atmospheric temperature inversion and inverse humidity phenomenon, through which heat and moisture were transported from the atmosphere to the land surface. The negative sensible heat flux remained steady at a large value. No similar phenomenon was observed at the Maqu grassland (Ao *et al.* 2008), which suggests that it could be linked to the presence of some small lakes. At night, the 'warm lake' effect raises the air temperature around the lakes, but the temperature of the land surface decreases quickly because of the surface's low soil moisture content and low thermal heat capacity. This makes the air

Figure 4. The daily variations of (a) the ground surface energy and (b) energy closure rate over Xihu desert wetland of Dunhuang for a summer continuous fine weather.

temperature higher than the ground surface temperature, resulting in the obvious negative sensible heat flux.

The energy balance closure problem was an important subject in this field test (Gao *et al.* 2003). The energy balance closure is based on the first law of thermodynamics, and requires the sum of the turbulent fluxes of sensible and latent heat, the sum of the net radiation, the ground heat flux and other forms of heat to be in balance. The formula is shown as follows:

$$H + LE = R_n - G - S - Q \quad (2)$$

where H is sensible heat flux, LE is latent heat flux, R_n is net radiation, G is soil heat flux, S is canopy heat storage, and Q is the sum of other forms of heat. Q was generally small and could be neglected. The rate of energy closure during the day at the field site was analyzed. Previous research (Moore 1986; McCaughey 1985) has indicated that canopy heat storage becomes significant when the canopy height exceeds 8 m, such as in a forest ecosystem. The vegetation in Xihu desert wetland is approximately 1 m high and S can be neglected. So the formula for the rate of energy closure can be expressed as $(H + LE)/(R_n - G)$, and the soil heat flux (G) can be represented by the observations made at depths of 0.05 m. The energy closure rate showed an obvious diurnal variation, and increased linearly with time from morning to

late afternoon (figure 3b). The mean energy closure rate for the observation period was 0.55, indicating a large degree of imbalance in the energy closure. There are several reasons for this:

- the accuracies of the recorded sensible and latent heat fluxes were lower at dawn due to weak atmospheric turbulence in the surface layer;
- the observation site was close to the lakes and therefore subject to medium- and small-scale circulation, such as a lake–land breeze caused by the surface heterogeneity in this area which triggered strong vertical movement (the vertical velocity could reach $0.79 \text{ m}\cdot\text{s}^{-1}$ in daytime), with the resulting vertical energy transport potentially affecting the surface energy balance;
- there were more grass roots at 0.05 m below the soil surface, which could have an impact on the soil heat flux, while in addition the soil heat flux measurements were based on the heat storage capacity of the soil heat flux plate (the soil heat storage capacity is closely related to soil temperature, humidity, and bulk density, and is usually very difficult to determine directly, thus leading to an error in the heat flux);
- Foken (2008) proposed a hypothesis in which the energy balance closure problem can be assumed to be a scale problem, and here there were a variety of instruments installed to observe the energy budget components, such as eddy correlation

instruments, radiometer, and soil heat flux plate, and since these different instruments had different landscape scales, this could have impacted on the energy closure rate, especially when considering the inhomogeneous underlying surface.

3.4 Variations of CO_2 flux and density

As shown in figure 5, the maximum absorption peak of carbon dioxide during the observation period in Xihu desert wetland was $-0.70 \text{ mg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (negative values indicate net CO_2 uptake and the positive values represent CO_2 emission), the mean value of CO_2 uptake was $0.20 \text{ mg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$; the maximum emission peak was $0.41 \text{ mg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and the mean value of CO_2 emission was only $0.11 \text{ mg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Therefore, this area was a ‘carbon sink’ during the observation period. Average diurnal variations of CO_2 flux showed an obvious fluctuation at the field site (figure 6), being negative during the day and positive at night. Figure 6 also shows that the maximum absorption of carbon dioxide occurred at about 11:00 hr, and the minimum value of average diurnal CO_2 flux (maximum CO_2 uptake) was $-0.31 \text{ mg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

Figure 5. The daily variations of the CO_2 flux and density over Xihu desert wetland of Dunhuang for a summer continuous fine weather.

Figure 6. The average diurnal variations of CO_2 flux and density over Xihu desert wetland of Dunhuang for a summer continuous fine weather.

In general, the duration of net carbon absorption was a little longer than the duration of net carbon emission each day, and the switch between the two regimes occurred at around sunrise and sunset (figure 6). The concentration of carbon dioxide was higher at night and lower in the daytime, and the minimum value of average diurnal CO_2 density occurred around 16:00 hr (figure 6). The concentration of carbon dioxide gradually decreased with time during the observation period (figure 5), which also indicated that the Xihu desert wetland ecosystem played a ‘carbon sink’ role.

4. Conclusions

After analyzing the microclimate and CO_2 flux characteristics in the Xihu desert wetland of Dunhuang, during fine weather conditions in summer, we can draw the following conclusions:

- The meteorological elements in Xihu desert wetland are strongly affected by lake–land breeze circulation, forming updrafts, and the friction wind velocity and vertical wind velocity were greater than those at Maqu grassland.
- The components of the ground surface radiation during the summer study period showed typical diurnal variations and the total solar radiation, and surface albedo were higher than those of Maqu grassland and Jinta Oasis. In addition, the ground upward long-wave radiation and atmospheric long-wave radiation were higher than those at other high altitude sites.
- The daily average net radiation in the Xihu desert wetland, Dunhuang, in summer was higher than those of the Maqu grassland and Jinta Oasis; the main turbulent exchange flux was of latent heat, and the sensible heat flux and latent heat flux were clearly negative at night, which indicated that there was an atmospheric temperature inversion and inverse humidity gradient in the surface layer of the Xihu desert wetland. The ground surface energy was strongly imbalanced, which might be related to the lake–land breeze and the measurement error of the soil heat flux.
- The maximum absorption of CO_2 occurred at around 11:00 hr in the Xihu desert wetland, and carbon absorption was greater than carbon emission. The concentration of CO_2 gradually decreased with time. Therefore, this area was a carbon sink during the observation period. Due to the limited observation stations and short observation time series, the results might have some limitations. In the future, there is a need for multiple approaches, long time scales, and comprehensive observations, which would help us further understand the relationship between the

land surface and atmosphere in the Xihu desert wetland.

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