J Arid Land (2015) 7(3): 318–327
doi: 10.1007/s40333-014-0079-4
jal.xjegi.com; www.springer.com/40333

Microclimate and CO_2 fluxes on continuous fine days in the Xihu desert wetland, China

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Abstract: The Xihu desert wetland is located in an extremely arid area in Dunhuang, Gansu province of Northwest China. The area is home to an unusual geographic and ecological environment that is considered unique, both in China and the world. Microclimate is not only related to topography, but is also affected by the physical properties of underlying ground surfaces. Microclimate and CO_2 flux have different characteristics under different underlying surface conditions. However, until now, few studies have investigated the microclimate characteristics and CO_2 flux in this area. The eddy covariance technique (ECT) is a widely used and effective method for studying such factors in different ecosystems. Basing on data from continuous fine days obtained in the Dunhuang Xihu desert wetland between September 2012 and September 2013, this paper discussed and compared the characteristics of daily microclimate variations and CO_2 fluxes between the two periods. Results from both years showed that there was a level of turbulent mixing and updraft in the area, and that the turbulent momentum flux was controlled by wind shear under good weather conditions. The horizontal wind velocity, friction wind velocity and vertical wind velocity were commendably consistent with each other. Air temperature in the surface layer followed an initial decreasing trend, followed by an increasing then decreasing trend under similar net radiation conditions. With changes in air temperature, the soil temperature in the surface layer follows a more obvious sinusoidal fluctuation than that in the subsoil. Components of ground surface radiation during the two study periods showed typical diurnal variations. The maximum diurnal absorption of CO_2 occurred at around 11:00 (Beijing time) in the Xihu desert wetland, and the concentrations of CO_2 in both periods gradually decreased with time. This area was therefore considered to act as a carbon sink during the two observation periods.

Keywords: eddy covariance; microclimate characteristics; CO_2 flux; extremely arid region; desert wetland; Dunhuang

Citation: QianQian GOU, JianJun QU, ZhiWen HAN. 2015. Microclimate and CO_2 fluxes on continuous fine days in the Xihu desert wetland, China. Journal of Arid Land, 7(3): 318–327. doi: 10.1007/s40333-014-0079-4

The physical properties of underlying surfaces determine the exchange of energy and materials between the soil, vegetation and the atmosphere. Such exchanges vary according to the microclimate, and in turn the microclimate characteristics are related to the physical properties of the underlying surfaces, in addition to the topography of a region. Arid and semi-arid regions cover about one-third of the Earth's surface, making them the largest biome type in the world (Reynolds, 2001). The ecosystems in such regions are particularly vulnerable to environmental constraints and human activities (Puigdefábregas and Mendizabal, 1998; Beer et al., 2009). Under the background of global climate change, arid ecosystems are suffering serious ecologyical problems in relation to arid climate characteristics such as lower precipitation, higher radiation, stronger evaporation, high temperatures and stronger winds. Due to glacial recession and rising snow lines in

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Received 2014-06-07; revised 2014-09-25; accepted 2014-10-17

recent years, the environments of these areas have deteriorated. Studied have reported that some lakes in these areas have rapidly decreased in surface area, and some have even dried up (Lake, 2003; Taylor et al., 2006; Finn et al., 2010). This has contributed to serious environmental and ecological degradation, and such eco-environmental problems will then have a profound impact on the global carbon cycle and climate change (Hastings et al., 2005).

The eddy covariance technique (ECT) is a widely used and effective method for studying microclimate characteristics and CO_2 flux in different ecosystems. Although many studies have been conducted in relation to microclimate characteristics and carbon fluxes using the ECT in different types of vegetation (Tenhunen et al., 1995; Miranda et al., 1997; Aussenac, 2000; Beringer and Tapper, 2000; Davies-Colley et al., 2000; Nijs et al., 2000; Hu et al., 2006; Beer et al., 2009; Niu et al., 2013), little research has been performed on vegetation types within extremely arid desert wetland ecosystems. Desert wetland vegetations have been endemic to adapt to extremely drought climate environments for a long time. The types of phytocoenosium mainly consist of xerophyte, halophyte and hygrophyte and are distributed in some bottomland in terminal lakes of some inland rivers.

The Xihu desert wetland is a national nature reserve, located approximately 120 km from Dunhuang city and situated at the western end of the Hexi Corridor in Gansu province. It is home to a typical wetland ecosystem, and is representative of a typical desert in an extremely arid region, making such an area both important and unique. As such, it is considered to be a natural laboratory for research into desert wetland ecosystems (Zheng et al., 2010). However, to date, there has been very little research carried out on the microclimate characteristics and CO_2 flux in this area. The research in this area could contribute to our understanding on the effects of microclimate characteristics and carbon sequestration associated with desert wetland ecosystems in extremely arid areas.

1 Study area and method

1.1 Study area

The study was carried out in the Xihu desert wetland, which is located in an extremely arid area measuring 66×10^6 km^2 in Northwest China. It borders the Kumtag Desert to the west, Aksay Kazak autonomous county to the south, and Xinjiang Uygur autonomous region to the north. The southern part of the area is elevated, while the northern part is essentially low-lying, and the central area is an alluvial plain. This study area is surrounded by gobi and deserts, and has a typical temperate continental climate. 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 inflate* (Chen et al., 2012). The area has an annual mean temperature of 9.9°C, with an average minimum daily temperature of –30°C in January, and an average maximum daily temperature of 40°C in July. The annual average wind velocity is 2.2 m/s and gales occur on a mean annual number of 15.4 d. Mean annual precipitation is a mere 39.9 mm, the mean annual evaporation capacity is 2,486 mm, and the drought index is greater than 16. The area has an annual sunshine duration of 3,115–3,246.7 h, the sunshine rate is 70%–73%, and the total annual radiation flux is 641.84 kJ/cm^2 (Qi et al., 2010; Chen et al., 2012). The latitude and longitude of the observation point are 40°20′16.4″N, 93°44′6.4″E, respectively. The area is surrounded by flat, open terrain at an elevation of 998 m asl.

1.2 Methods and data analysis

In this paper, data of diurnal and daily variations in micrometeorological variables, ground surface radiation balance, daily CO_2 flux and density measurements were collected in the Xihu desert wetland during two periods of continuous fine weather from September 2012 and September 2013.

The ECT was used in the establishment of instruments for data collection. A three-dimensional sonic anemometer (CSAT3, Campbell Scientific, Logan, USA) was used to measure fluctuations in temperature, wind velocity and wind direction. An open-path flux sensor was installed 3 m above the soil surface (above *Phragmites australis*, which stands approximately 100 cm tall, and *Alhagi sparsifolia*, which is approximately 40 cm tall), and orientated in the direction of the prevailing winds. CO_2 concentrations and water vapor were measured using an open-path infrared gas analyzer (LI-7500, LiCor, Lincoln, USA), which was calibrated at regular intervals for CO_2 and water vapor 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. A four-component net radiometer (Rn) (CNR-1, Kipp & Zonen, the Netherlands) was placed 3 m above the soil surface. Air temperature (T_{air}) and humidity were measured at a height of 3 m from a tower (HMP45C, Vaisala Inc., Helsinki, Finland). Two self-calibrating soil heat flux sensors (HFP01) were mounted at 0.05 and 0.10 m below the soil surface, and the soil temperature profile (109-L, Campbell Scientific Ltd., Edmonton, Alberta, Canada) and soil water content (SWC) profile (EnviroSMART, Campbell, Scientific Ltd., Edmonton, Canada) were monitored adjacent to the micrometeorological tower. Soil temperatures were measured at five depths (0.10, 0.20, 0.40, 0.60 and 1.00 m), and the average soil temperature was determined at a depth of 0.20 m. SWC was also measured at five depths (0.10, 0.20, 0.40, 0.60 and 1.00 m). Precipitation was collected and measured by a rain gauge (TE525MM, Texas Electronics Inc., Dallas, USA) mounted 0.7 m above the soil surface.

Post-processing software, EdiRe (University of Edinburgh, UK), was used to process raw data. On the basis of the recommendations of Lee et al. (2006), the following processing steps were applied: spike removal, auto-detection of the time delay between different sensors, conversion of the temperature measured 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 also used to compensate for missing data (Valentini et al., 2000; Falge et al., 2001; Gilmanov et al., 2007).

2 Results

2.1 Microclimate and soil temperature

Average diurnal variations of T_{air} in the surface layer were found to be similar in the two study periods (September 2012 and September 2013) (Fig. 1a). Average daily T_{air} values ranged from a minimum of 2.34°C (September 2012) and 1.75°C (September 2013) to a maximum of 32.16°C (September 2012) and 30.70°C (September 2013) (Figs. 1b and c). The mean T_{air} values were 18.12°C and 17.13°C in September 2012 and September 2013, respectively. The minimum daily T_{air} during the observation periods occurred at approximately 07:00 (Beijing time, similarly hereinafter), and the maximum between approximately 16:00–18:00. Daily T_{air} in the surface layer firstly followed a decreasing trend, then an increasing trend followed by a subsequent decreasing trend under similar net radiation conditions during the two observation periods.

In September 2012 and September 2013, the horizontal wind velocity exhibited obvious diurnal patterns during the continuous fine weather throughout the study period (Fig. 2). A considerable number of friction wind velocities were greater than 0.1 m/s, and the maximums were 0.79 and 0.85 m/s in September 2012 and September 2013, respectively. This indicates a level of turbulent mixing, justifying the reliability of the observation results. It also shows that the horizontal wind velocity is in accord with the frictional wind velocity in both periods, demonstrating that the turbulent momentum flux was controlled by wind shear during the good weather conditions. Most vertical wind velocities were positive at the field site (Fig. 2), and the mean and maximum daily vertical wind velocities were 0.19 and 0.78 m/s (September 2012) and 0.14 and 0.85 m/s (September 2013), respectively, and associated with strong updrafts.

The observation of regular changes in soil temperature at different depths in September 2012 and September 2013 showed that the soil temperature varied sinusoidally in the layers located at 10 and 20 cm below the surface, and that the peak soil temperature in the layer 20 cm below the surface lagged behind that in the layer at 10 cm; both decreased slowly with time (Figs. 3a and b). However, there was no sinusoidal variation in the soil temperature in the layer 40 cm below the surface. The explanation for the discrepancy between the layers is that those located 10 and 20 cm below the surface received more heat than the deeper

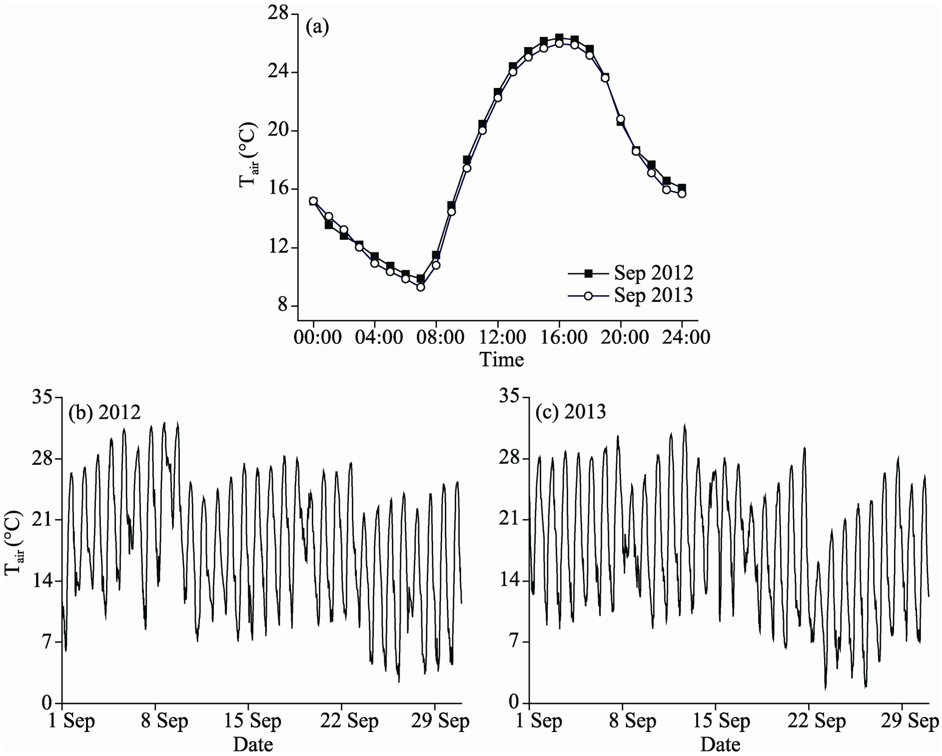

Fig. 1 Average diurnal air temperature (T_{air}; a) and daily variation in T_{air} (b and c) on continuous fine days in September of two consecutive years in the Xihu desert wetland

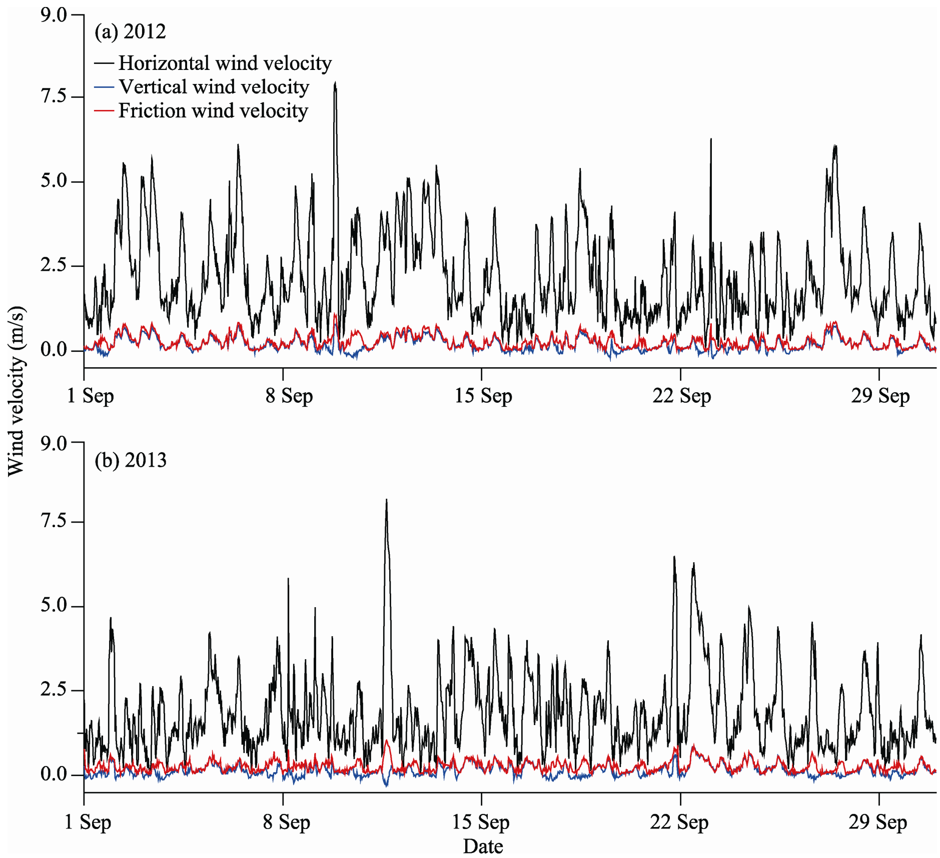

Fig. 2 Daily variations in horizontal, frictional and vertical wind velocities on continuous fine days in September of two consecutive years in the Xihu desert wetland

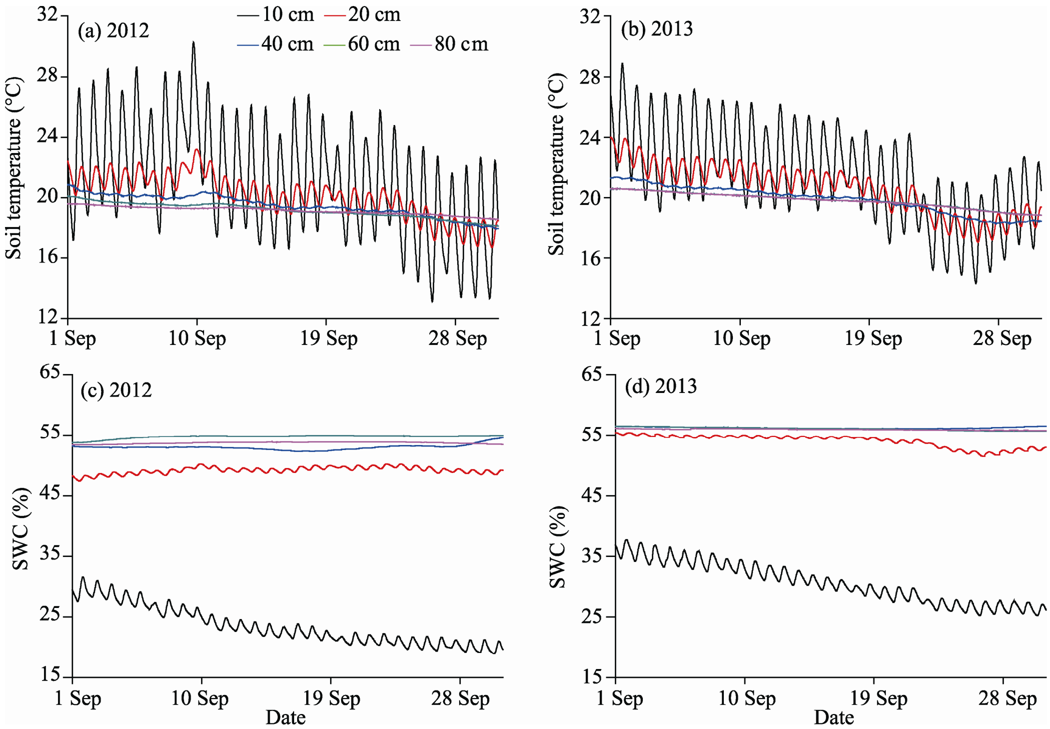

Fig. 3 Daily variations in soil temperature (a, September 2012; b, September 2013) and soil water content (c, September 2012; d, September 2013) within different soil depths

layers in relation to solar heating, thus the temperature in the upper two layers followed a more obvious sinusoidal pattern than that in the subsoil.

The SWC differed in the five soil depths in both September 2012 and September 2013 (Figs. 3c and d). In the layer 10 cm below the surface, SWC varied periodically and sinusoidally with time, but there was little change in SWC in the other layers.

2.2 Characteristics of ground surface radiation balance

Figure 4 shows the daily variations in several components of the ground surface radiation throughout September 2012 and September 2013, which exhibited significant regularity over the periods of continuous fine weather in the study area. The daily variations in total solar radiation (downward shortwave radiation as shown in Fig. 4) ranged from 0 to 1,096.92 W/m^2 in September 2012, and from 0 to 1,133.48 W/m^2 in September 2013. Both study periods have obvious diurnal variations (higher solar radiation during daytime and zero at nighttime), and the maximum in both periods occurs at around 14:00. Diurnal variations in atmospheric long-wave radiation at the field site were small (Fig. 3a), varying from 289.60 to 450.69 W/m^2 in September 2012, and from 287.46 to 440.75 W/m^2 in September 2013; both sites showed lower values in the morning than in the evening.

The value of reflected radiation was zero during the night in both study periods, and this is related to the lack of solar downward shortwave radiation at night (Fig. 4). It also shows that the amount of reflected radiation rises slowly after sunrise, reaching a maximum before or after noon. The diurnal variation in reflected radiation (upward short-wave radiation as shown in Fig. 4) ranged from 0 to 207.31 W/m^2 and from 0 to 190.39 W/m^2 in September 2012 and September 2013, respectively, and both of the maximum values of reflected radiation in the two study periods occurred at around 14:00 every day.

From Fig. 4, it can be seen that the surface longwave radiation in the Xihu desert wetland exhibited regular daily variation in both study periods. Although the surface temperature was very high during the study periods, the diurnal temperature range was higher (because the surface temperature was lower at

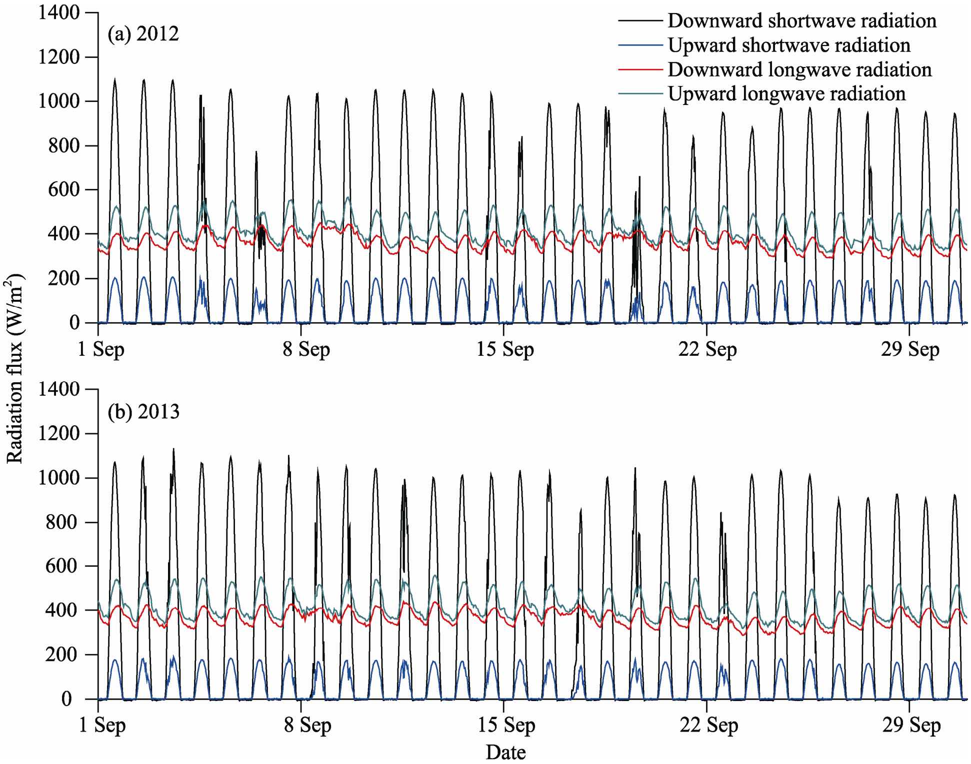

Fig. 4 Daily variations in the ground surface radiation on continuous fine days in September of two consecutive years in the Xihu desert wetland

night, and therefore, the surface long-wave radiation was also low). It can also be seen that surface long-wave radiation follows an obvious diurnal pattern, varying from 317.04 to 565.90 W/m^2 in September 2012, and from 318.46 to 560.14 W/m^2 in September 2013.

The diurnally integrated values of total solar radiation, atmospheric long-wave radiation, reflected radiation and ground upward long-wave radiation were respectively 24.63, 31.32, 5.06 and 36.17 MJ/(m^2·d) in September 2012, and 25.25, 31.58, 4.61 and 36.37 MJ/(m^2·d) in September 2013. It can thus be seen that 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 that reflected radiation contributed the least to the balance.

2.3 Variations in CO_2 flux and density

As shown in Fig. 5, in September 2012, the maximum daily absorption peak of CO_2 was –0.46 mg/(m^2·s) (negative values indicate net CO_2 uptake, and positive values represent CO_2 emissions) and the mean daily value was –0.18 mg/(m^2·s); the maximum daily emission peak was 0.34 mg/(m^2·s), and the mean daily value was only 0.10 mg/(m^2·s). In September 2013, the maximum daily absorption peak of CO_2 was –0.53 mg/(m^2·s), the mean daily value was –0.21 mg/(m^2·s); the maximum daily emission peak was 0.57 mg/(m^2·s), and the mean daily value was only 0.12 mg/(m^2·s). The CO_2 flux showed obvious diurnal variations at the field site (Fig. 5), showing positive values during the day and negative values at night. Maximum absorption of CO_2 occurred at 11:00 in both study periods, and in general the duration of net carbon absorption continued for slightly longer than the duration of net carbon emission each day, and the switch between the two regimes occurred at around sunrise and sunset in the two study periods. Concentrations of CO_2 were higher during the night and lower in the daytime, at minimum levels during the evening, and gradually decreased with time during the two observation periods, indicating that the desert wetland ecosystem played the role of a carbon sink.

3 Discussion

As an important factor in the observation of microclimate and CO_2 flux, friction wind velocity shows the

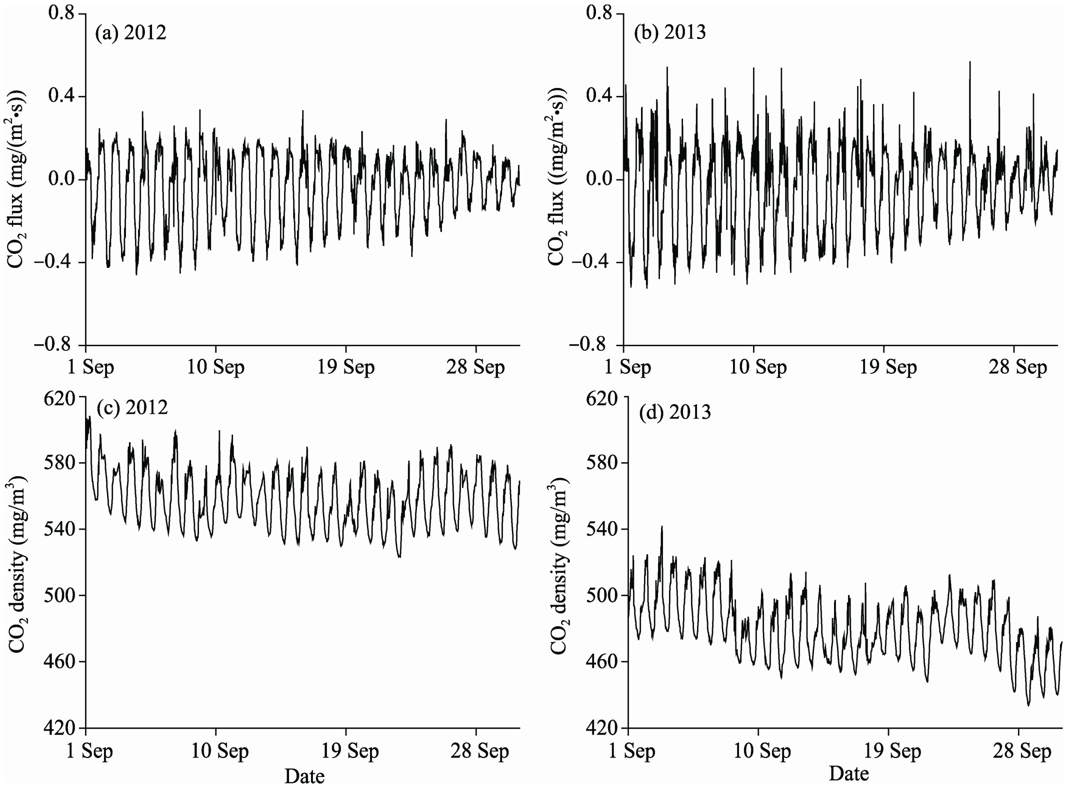

Fig. 5 Daily variations in CO_2 flux (a and b) and CO_2 density (c and d) on continuous fine days in September of two consecutive years in the Xihu desert wetland

transportation and dispersion capacity in different spatial directions, and serves as a turbulent velocity scale (Li et al., 2012). In our study, the horizontal wind speed is consistent with friction wind velocities in the two study periods; the resulting fit demonstrates that the turbulent momentum flux was controlled by wind shear during the good weather conditions (Hu et al., 1992). In addition, according to the results of friction wind velocity in the two study periods, the level of turbulent mixing is in agreement with observations in the Xihu desert wetland ecosystem. Discrepancies in the values of many factors, such as solar radiation, atmospheric movement and underlying surface properties, can cause fluctuation in T_{air}, but the daily variations in T_{air} were similar in the two studies owing to the similar amount of solar radiation absorption.

The soil temperatures in the two periods present similar diurnal variations with a similar change of T_{air} and solar radiation (Fig. 6). This study revealed that soil temperatures change sinusoidally with time, and

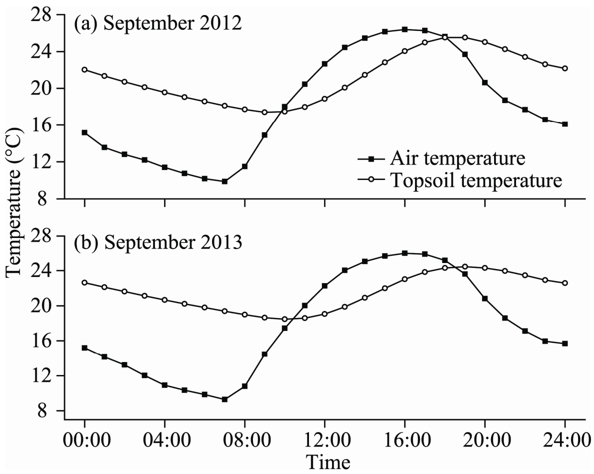

Fig. 6 Diurnal variations in T_{air} and topsoil temperatures on continuous fine days in September of two consecutive years in the Xihu desert wetland

that the amplitude of sine waves decreases with increasing soil depth; the amplitude is approximately zero when the soil reaches a certain depth, which is consistent with the results of Dai et al (Dai et al., 2009). In addition, the SWC also shows regular daily variation characteristics, particularly the sinusoidal changes in the surface layer (which is consistent with the study by Du et al. (2005)), mainly because the sun heated the surface soil and increased the evaporation of soil water. In relation to this, soil evaporation was found to be low in other soil layers owing to the reduced amount of solar heating at such depths, and the SWC was therefore higher than that of the surface layer.

Total solar radiation varies with changes in solar altitudinal angle, air density, cloud fraction and other parameters. It is the dominant term used in relation to surface radiation balance and largely responsible for any observed variability seen in other terms. In this study, total solar radiation had an obvious diurnal variation in both study periods owing to the continuous fine weather, and such a result is consistent with other related researches (Zhang et al., 2006; Gu et al., 2013). Atmospheric long-wave radiation is highly sensitive to moisture content (Li et al., 2012). Meanwhile it is also affected by atmospheric density, moisture content, aerosol concentration, cloud and certain other factors. In this study, 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 it would have been at higher altitudes (Ao et al., 2008). The ground upward long-wave radiation can be repressented as a mathematical formula:

$$F=\varepsilon\rho T_g^4. \qquad (1)$$

Where ε is emissivity, ρ 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 a land surface cover. The surface temperature therefore determines the strength of the surface long-wave radiation (Li et al., 2012). The surface long-wave radiation in our study area was higher than that at other higher altitudes (Ao et al., 2008) owing to the low altitude of the measurement station.

Changes in climatic conditions with time lead to variations of CO_2 flux. A difference in temperature is one of the main factors which can cause changes of the amounts of CO_2 absorbed and released in particular terrestrial ecosystems (Qiao et al., 2011). In this study, there was a large temperature difference between daytime and nighttime in the study area, with a nighttime temperature of <15°C, which is signifycantly lower than daytime temperature of >35°C. This is one of the significant factors related to the relatively high net CO_2 absorption during the observation period. In the daytime, sufficient light and suitable temperature were beneficial for photosynthesis and ensured that plants absorbed more CO_2; however, the lower nighttime temperatures weakened the respiration of plants and edaphon.

4 Conclusions

On the basis of analyzing the microclimate and CO_2 flux characteristics of the Xihu desert wetland during fine weather conditions in autumn (September 2012 and September 2013), the following conclusions can be drawn. First, a level of turbulent mixing and updraft was recorded in the wetland. The horizontal wind velocity, friction wind velocity and vertical wind velocity were commendably consistent with each other, and the turbulent momentum flux was controlled by wind shear during the good weather conditions. The T_{air} in the surface layer followed a decreasing trend at first, and then an increasing trend followed by a decreasing trend again under similar net radiation conditions. The soil temperature in the surface layer followed a more obvious sinusoidal fluctuation than in the subsoil with a change in T_{air}, and the soil water content in the surface layer also showed a more obvious fluctuation than that of the subsoil layers under the influence of solar radiation and heating. Second, the components of ground surface radiation during the two study periods showed typical diurnal variations; the diurnally integrated values of total solar radiation, atmospheric long-wave radiation, reflected radiation and ground upward long-wave radiation were 24.63, 31.32, 5.06 and 36.17 MJ/(m^2·d), respectively, in September 2012, and 25.25, 31.58, 4.61 and 36.37 MJ/(m^2·d), respectively, in September 2013. Third, the maximum diurnal absorption of CO_2 occurred at around 11:00 in both study periods, and carbon absorption was greater than carbon emission. In addition, the concentration of CO_2 gradually decreased with time. This area is therefore considered to have acted as a carbon sink throughout the two observation periods.

It is noteworthy that, owing to the limited number of observation stations and the short observation time series, the results may have certain limitations. The future studies should use multiple approaches, long time scales and comprehensive observations, all of which would assist in understanding the relationship between the land surface and the atmosphere in the Xihu desert wetland.

Acknowledgements

This work was supported by the National Science-technology Support Plan Projects "Key Techniques Research and Demonstration of Ecological Remediation of Dunhuang" (2012BAC08B07). We sincerely thank Prof. JieMin WANG for his contribution during the data processing.

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