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ORIGINAL PAPER

Diurnal and seasonal variations of surface albedo in a spring wheat field of arid lands of Northwestern China

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Abstract Surface albedo greatly affects the radiation energy balance of croplands and is a significant factor in crop growth monitoring and yield estimation. Precise determination of surface albedo is thus important. This study aimed to examine the influence of growth stages (tillering, jointing, heading, filling and maturity) on albedo and its diurnal asymmetry by measuring diurnal albedo variations. Results indicated that the daily mean surface albedo generally exhibited an increased tendency during tillering to heading but decreased after heading. Surface albedos were much higher in the morning than the corresponding values of the same solar elevation angles in the afternoon when the solar elevation angle was less than 40°, indicating a diurnal asymmetry in surface albedo. However, less difference was found in surface albedos between forenoon and afternoon when the solar elevation angle was greater than 40°. Dew droplets on the leaf surface in the morning were assumed to be the main factor resulting in the diurnal asymmetry in albedo of spring wheat.

Key words Spring wheat · Surface albedo · Growth stage · Asymmetry · Dew · Solar elevation angle

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Introduction

Solar radiation is the main source of the Earth's surface energy. After interacting with the atmosphere (being partly absorbed, scattered and reflected by it), a fraction of the incident solar radiation is absorbed by the Earth's surface to heat the surface or evaporate water, either directly from the soil or via evapotranspiration, and the remaining is reflected back (Garratt 1992; Minnis et al. 1997). Surface albedo is defined as the ratio of the reflected to the incoming shortwave (0.3–3 μm) solar radiation striking a surface. It directly controls radiative energy distribution at the surface, which, in turn, affects the physical, physiological, and biogeochemical processes (surface temperature, evapotranspiration, energy balance, photosynthesis and respiration, etc.) of an ecosystem (Yin 1998; Wang et al. 2001, 2005). Generally, bare surface albedo is controlled by soil moisture, surface type, solar elevation angle and weather conditions, etc. (Zuo et al. 1991), and the diurnal trend of surface albedo is assumed to be symmetrical when surface albedo depends solely on the solar elevation angle (Minnis et al. 1997). For vegetated surfaces, fractional canopy cover and plant phenology are also controls (e.g., Jacobs and van Pul 1990; Minnis et al. 1997; Song 1999). Parameterization of surface albedos in atmospheric process and climate models generally assume that the surface albedo depends only on the solar elevation angle, suggesting that the diurnal variation of surface albedo is symmetrical and parabolic (Minnis et al. 1997). However, there is accumulating evidence suggesting a diurnal asymmetry in vegetated surface albedo (e.g., Stanhill et al. 1968; Ripley and Redmann 1976; Al-Yemeni and Grace 1995; Minnis et al. 1997; Dexter 1999; Song 1999; Grant et al. 2000; Wen et al. 2009). This evidence can be sorted into two categories according to the factors resulting in the asymmetry. On one hand, afternoon albedos are either higher (Ripley and Redmann 1976; Song 1998; Grant et al. 2000) or lower (Song

1998) than morning albedos, which depends on the alignment of vegetation and the leaf angle in response to the direction and speed of prevailing winds. On the other hand, afternoon albedos are lower than morning albedos because of dew droplets on the grass and crop surfaces that tend to increase albedo at visible wavelengths in the morning (Pinter 1986; Minnis et al. 1997; Wen et al. 2009). As aforementioned, factors resulting in the diurnal asymmetry in surface albedo were diverse, and understanding thereof was limited due to insufficient research. Thus, further studies are required to contribute to a clearer description of the asymmetry in albedo and the causative factors.

Surface albedo of a cropland is not constant, but changes considerably during the growing season (Jacobs and van Pul 1990; Song 1999; Oguntunde and van de Giesen 2004), suggesting different solar energy demands among growth stages. The variations of surface albedo with growth stage and the issue of diurnal albedo symmetry or asymmetry are important in environmental crop production models (Idso et al. 1978), eco-hydrological models (Yin 1998) and in land surface parameterizations (Song 1998). Field observations can obtain accurate data and provide a means to assess the relationship between vegetated surface albedo and phenology (Song 1999; Oguntunde and van de Giesen 2004). The current research aims to present the seasonal course of albedo and to analyze the diurnal albedo asymmetry and the factors causing this asymmetry, by observing the albedo of spring wheat during the growing season.

Materials and methods

Site description

The field experiments were conducted at Cropland Ecosystem Comprehensive Observation Field, Shapotou Desert Research and Experiment Station (SDRES) of Chinese Academy of Sciences (37°32′ N, 105°02′ E, 1,300 m a.s.l.), at the southeastern fringe of the Tengger Desert in Northwestern China. Based on the 50-year (1955–2005) meteorological record of SDRES, the annual mean precipitation is only 191 mm, with 80 % of rain falling between July and September, and precipitation is the only source of soil water replenishment. The monthly mean air temperature is 10.4 °C, with an average maximum air temperature 24.7 °C in July and an average minimum air temperature −6.1 °C in January. The potential evapotranspiration is as high as 2,500 mm during the growing season (April–October).

Experimental design and data collection

During April–July 2009, the surface albedo was measured in the growth stages as listed in Table 1 over a 10 m×10 m spring wheat field by using two EKO MR-32 pyranometers (spectral range: 0.3–2.8 μm; accuracy: ± 2.5 %; sensitivity: 7 mV kW^{-1} m^{-2}) mounted on the top of a tripod 50 cm to the spring wheat canopy, one hemisphere sensor of the pyranometer pointed upward to measure incoming radiation flux R↓, and another one pointed downward to simultaneously measure the reflected radiation flux R↑. Surface albedo α is calculated as the ratio of R↑/R↓. The measurements of surface albedo were taken at 30 min intervals from 08:30 to 17:30 Beijing time (about 07:30 to 16:30 local time) on 2 successive clear days for each growth stage except for a 1-day pause in heading stage (Table 1). Matthias et al. (1999) and Sailor et al. (2006) present detailed descriptions of ground-based albedo measurement using pyranometers. Song (1999) and Oguntunde and van de Giesen (2004) showed good application of albedo measurements in crop fields using similar tools.

The daily average surface albedo was calculated using the following equation (Fu et al. 1994):

$$\alpha = \sum_{i=1}^{N} R\uparrow_i \cdot \Delta t_i \Big/ \sum_{i=1}^{N} R\downarrow_i \cdot \Delta t_i \tag{1}$$

where α is the daily average surface albedo, $R\uparrow_i$ is the reflected solar radiation (W m^{-2}), $R\downarrow_i$ is the incoming solar radiation (W m^{-2}), N is the number of albedo observations in the daytime, and Δt_i is the time step (min) between two consecutive observations (from i−1 to i).

The crop height, the average of the heights from the ground to its highest point of ten plants selected randomly within the spring wheat field, was measured with a ruler with a resolution of 1 mm on each observation day. Moreover, surface soil moisture (0–2 cm) values were determined from hourly gravimetric samplings at five locations within the plot immediately after albedo data collection. It was assumed that soil moisture was fairly homogeneous to a depth of at least 2 cm. Soil samples were taken back to the laboratory, where they were weighed and reweighed before and after 24 h of drying in an oven at 105 °C, respectively. Gravimetric soil moisture was then calculated as the ratio of water mass to the mass of dry soil. Sixty-minute average

Table 1 Observation days during growth stages of spring wheat in 2009

Growth stage	Date	Crop height (cm)
Tillering	7 and 8 April	14
Jointing I	20 and 21 April	20
Jointing II	5 and 6 May	37
Heading	18 and 20 May	58
Filling	12 and 13 June	81
Maturity	2 and 3 July	80

data of surface air temperature, relative humidity and wind speed at 2 m height above soil surface were derived from the automatic weather station (WS-STD1, Campbell Scientific, Loughborough, UK) 200 m from the spring wheat field.

Results

Diurnal and seasonal variations of surface albedo

Albedo data of 2 clear days for each growth stage of spring wheat (tillering, jointing, heading, filling and maturity) were chosen for analysis and the averaged albedo over the 2 days was considered as the representative albedo value for a specific growth stage. Note that we empirically divided jointing stage into jointing I and jointing II stage due to the rapid growth rate of spring wheat and rapid change of surface cover in jointing stage. Figure 1 illustrates the diurnal variation of surface albedo at different growth stages as listed in Table 1. The diurnal trend of surface albedo showed similar diurnal curves, with higher albedo values in the morning and afternoon and lower values about local noon, mimicking an upward facing parabolic curve.

Figure 2 presents the regression relationship between daily average albedo and crop height. Crop height increased until filling and then varied little from filling to maturity (Table 1). The seasonal changing course of surface albedo displayed a downward facing parabolic curve with crop height, i.e., the daily mean surface albedo showed an increased tendency during tillering to heading but decreased after heading, which agrees with Gutman et al. (1989) and Song (1999). The order of daily mean albedo among the growth stages were: heading (0.209)>jointing II (0.207)> tillering (0.186)>maturity (0.184)>jointing I (0.176)>filling (0.174).

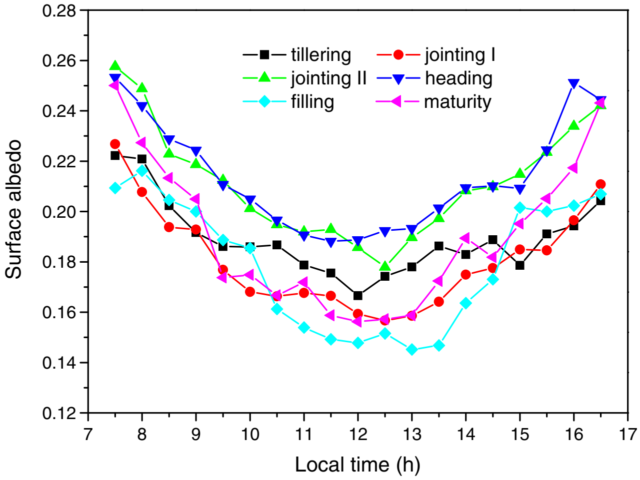


Fig. 1 Diurnal variations of surface albedo of spring wheat at different growth stages

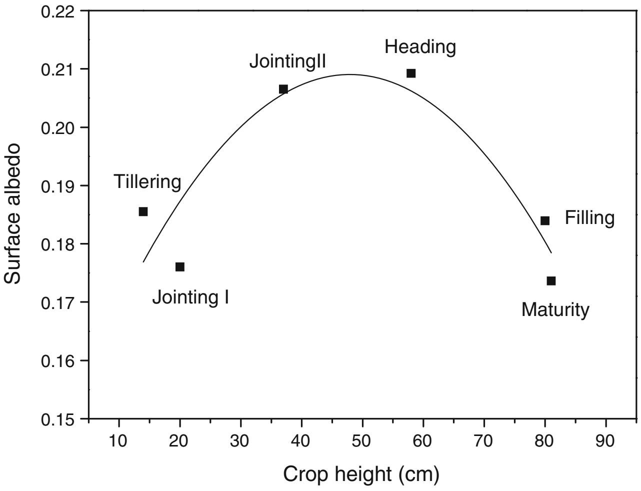


Fig. 2 Relationship between daily average albedo and crop height during the growing season of spring wheat

Diurnal asymmetry in surface albedo

Comparisons of AM and PM surface albedos in each growth stage derived from selected clear days are illustrated in Fig. 3. AM in Fig. 3 refers to the time period between 07:30 and 12:00 local time, while PM refers to the period between 12:00 and 16:30 local time. The AM albedos at a given solar elevation angle were greater than that of PM albedos when the solar elevation angles were low (e.g., 30°), implying a diurnal asymmetry of surface albedo about local noon. This phenomenon occurred on nearly all the observation days (not very pronounced in maturity stage), thus we hypothesized that the diurnal asymmetry of surface albedo in the early morning with low solar elevation angles is common throughout the growing season.

To quantify the diurnal asymmetry of surface albedo, the equation below (Dexter 1999) was introduced, which compares AM and PM albedos at the same elevation angle,

$$\Delta\alpha_{\theta} = \frac{\alpha_{AM,\theta} - \alpha_{PM,\theta}}{0.5(\alpha_{AM,\theta} + \alpha_{PM,\theta})} \qquad (2)$$

where $\Delta\alpha_{\theta}$ is the percentage difference (%) between AM and PM surface albedos, $\alpha_{\mathrm{AM},\theta}$ is the AM surface albedo at a given solar elevation angle θ, $\alpha_{\mathrm{PM},\theta}$ is the PM surface albedo at the same solar elevation angle with $\alpha_{\mathrm{PM},\theta}$.

Figure 4 indicates the percentage difference between AM and PM surface albedos. When the solar elevation angle was lower than 40°, $\Delta\alpha_{\theta}$ values were mostly greater than 0, suggesting that AM albedos were greater than PM albedos at the same solar elevation angle. However, $\Delta\alpha_{\theta}$ values then began to slightly fluctuate along with $\Delta\alpha_{\theta}=0$ when the solar elevation angle was greater than 40°. Those results indicated there was an asymmetry in surface albedo when the solar elevation angle was less than 40°, which was similar to the findings of Minnis et al. (1997) and Wen et

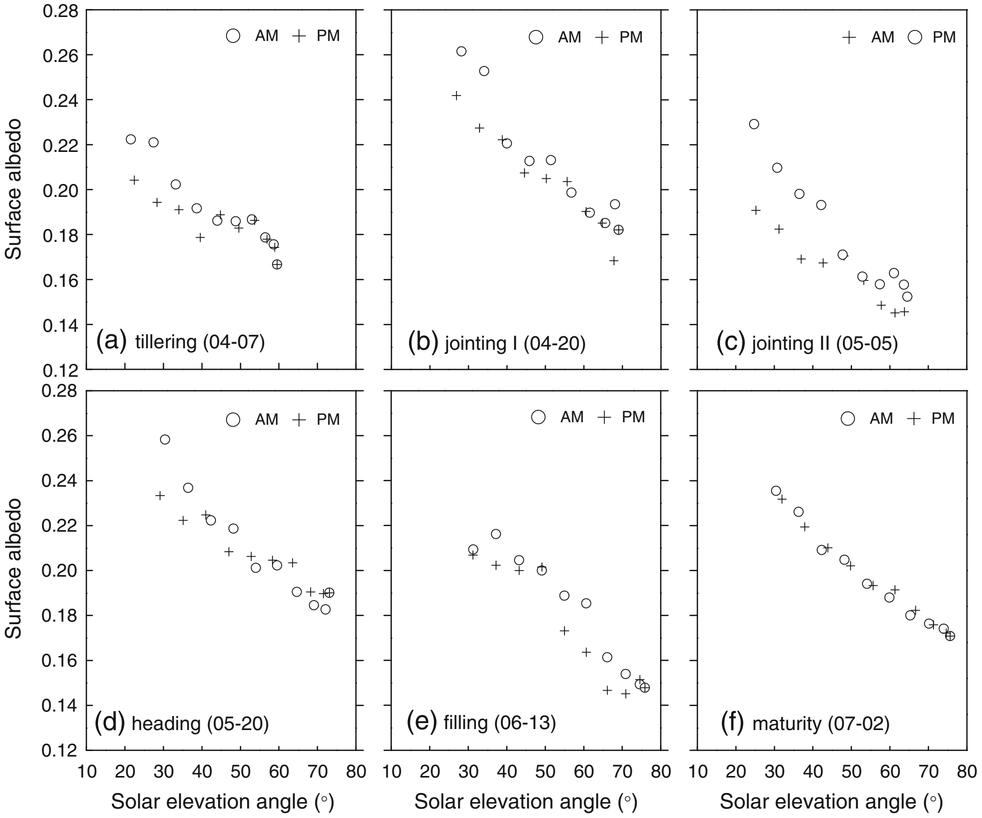


Fig. 3 Comparison of AM and PM surface albedos on 6 selected clear days at different growth stages of spring wheat

al. (2009). The daily average values of $\Delta\alpha_\theta$ were 4.0 % during tillering stage, 10.0 % in jointing I stage, 4.7 % in jointing II stage, 0.3 % in heading stage, 4.9 % in filling stage and 1.0 % in maturity stage. The average value of $\Delta\alpha_\theta$ during the whole growing season was as high as 11.6 % when solar elevation angle was lower than 30°. The surface albedo became symmetrical when the solar elevation angle was greater than 40°.

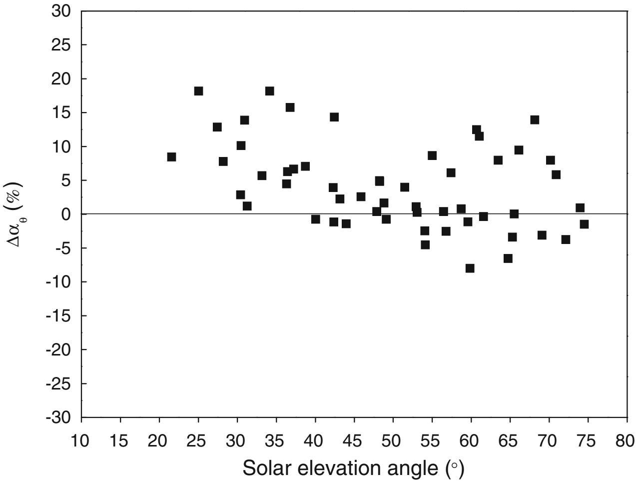
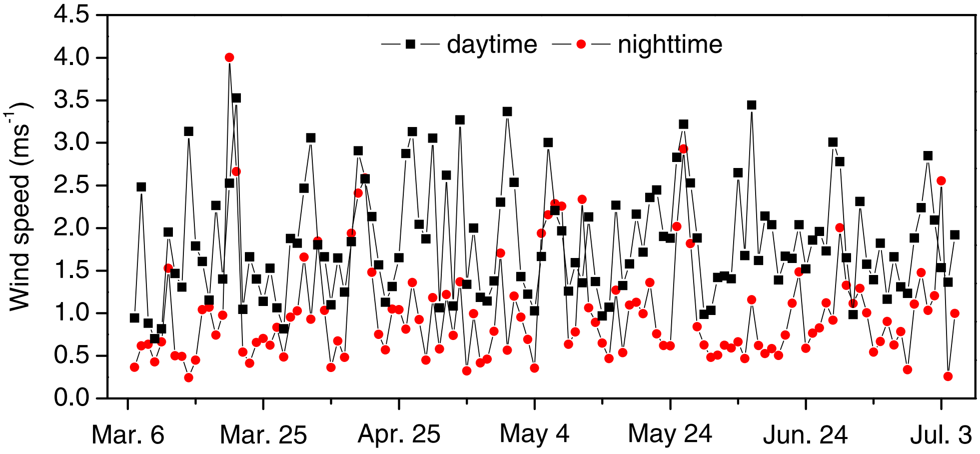


Fig. 4 Percentage difference between the forenoon and afternoon albedos on 6 selected clear days at different growth stages of spring wheat

Discussion and conclusions

Variations in the albedo of spring wheat were found both in a single observation day and during the whole growing season. The upward facing parabolic curve of diurnal surface albedo (Fig. 1) was caused mainly by solar elevation angle under clear sky conditions. However, factors resulting in the seasonal change of surface albedo, which showed a downward facing parabolic curve with crop height (Fig. 2), were more complex. During the growing season of spring wheat, daily mean solar elevation angle also changed over time with the highest solar elevation angle around 22 June (Iziomon and Mayer, 2002). Therefore, taking no account of the phenological changes, the albedos would theoretically decrease before around 22 June and then increase thereafter. However, our results are not in agreement with this prediction, as can be seen in Fig. 2, in which it can be seen that the seasonal changing course of surface albedo displayed a downward facing parabolic curve with crop height. We thus consider that the seasonal variations of surface albedos can be attributed mainly to both solar elevation angle and phenological changes, which is also evidenced by Song (1999) who examined the seasonal variation in albedo caused by phenological changes in a wheat field at a constant solar elevation angle of 70°. Solar energy is the main surface energy

Fig. 5 Comparison of daytime and nighttime wind speed during the growth period of spring wheat. Daytime wind speed here refers to the average value from 7:00 to 19:00 and nighttime wind speed refers to the average value from 19:00 to 7:00 the next morning

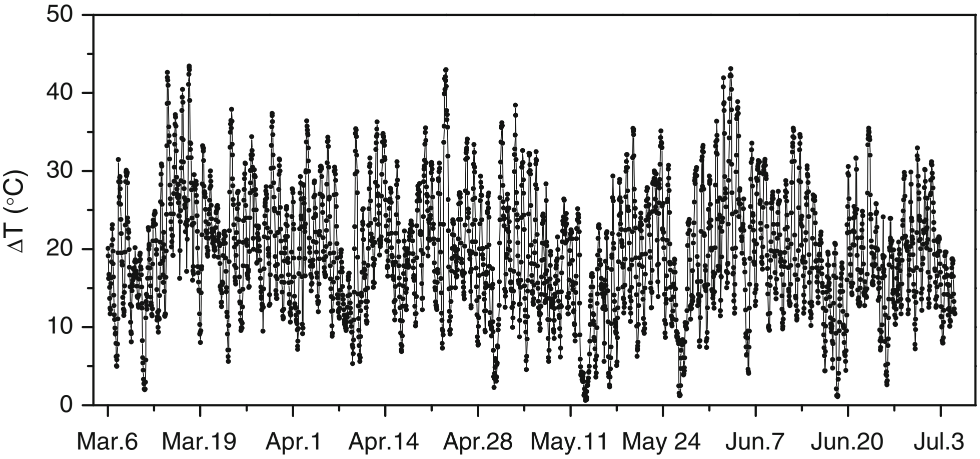


source of croplands, and surface albedo determines the solar radiation and energy distribution. The current research shows that surface albedo in the spring wheat field is externally sensitive to growth stage. Therefore, the changing course of surface albedo throughout the growing season of spring wheat reveals varied requirements in radiation energy during different growth stages, which can be important in crop growth monitoring and radiation budget calculations.

Our observations were made on clear days, which removed the complex influence of weather conditions on albedo measurements. Crop height was assumed to be identical within a single day. Previous studies had shown that soil moisture in shallow soil profile (<2 cm) strongly affects surface albedo, i.e., surface albedo decreased with the increasing of surface soil moisture content (e.g., Idso et al. 1975; Gu et al. 2000; Matthias et al. 2000; Liu et al. 2002; Lobell and Asner 2002; Wang et al. 2005). The albedos during tillering and jointing I stage were controlled jointly by plant canopy and the bare soil exposed to pyranometer sensor. As the season progresses, however, surface albedo is controlled predominantly by the physical condition of leaves and the structure of the crop during other growth stages when the leaf layer fully covered the soil, as also indicated by e.g., Jacobs and van Pul (1990) and Song (1998). The influence of soil moisture on albedo was therefore assumed to be negligible during jointing II to maturity due to fully covered plant canopy over the soil surface. Moreover, our measurements indicated that soil moisture decreased exclusively in the daytime. If soil moisture was a control factor on diurnal asymmetry of albedo, PM surface albedos should be greater than AM albedos, which is not the case in our results. Thus, soil moisture cannot be used to explain the diurnal asymmetry of albedo, with AM albedo values higher than PM values.

According to previous explanations of the diurnal asymmetry of surface albedo (e.g., Stanhill et al. 1968; Ripley and Redmann 1976; Al-Yemeni and Grace 1995; Minnis et al. 1997; Dexter 1999; Song 1999; Grant et al. 2000; Wen et al. 2009), the causative factors are either wind condition (wind speed and wind direction) or early morning dew droplets on the plant leaf when surface soil moisture was not taken into account. Among these factors, Song (1998) observed an asymmetrical albedo both in the corn field and

Fig. 6 Time series of the difference between air temperature and dew point temperature during the growth period of spring wheat



wheat field. This was attributed to a reclined canopy in moderate to strong wind. AM albedos were higher than PM albedos when there was a strong east component in the prevailing wind and the canopy bent westward, and AM albedos were lower than PM albedos when there was a strong west component in the prevailing wind and the canopy bent eastward. Song et al. (1997) also found that higher surface albedos during the morning (rather than the afternoon) at the tallgrass-prairie sites were associated with strong prevailing winds (greater than 6 m s^{-1} at 10 m height) from the southeast, and almost symmetrical whenever the winds were weak (less than 3 m s^{-1} at 10 m height). Figure 5 presents a comparison of daytime and nighttime wind speed during the growth period of spring wheat. We observed no strong prevailing wind in the AM and PM in the research area, respectively. The average wind speed was 1.46 m s^{-1} during the observation period, 89 % of the wind speed delivered less than 3 m s^{-1}. The average daytime wind speed was 1.83 m s^{-1}, and the average nighttime wind speed was 1.02 m s^{-1} . Moreover, if prevailing wind is the causative factor for diurnal albedo asymmetry, the albedos in the AM should be exclusively higher or lower than the corresponding PM albedos because the plant canopies would recline to a specific direction according to the prevailing wind. Our results, however, found that the diurnal albedo asymmetry occurred only when the solar elevation angles were less than 40°. We thus inferred that wind regime was not the main causative factor for diurnal albedo asymmetry in this study area.

Minnis et al. (1997) suggested that for regions like the southern Great Plains in North America, the albedo tends to be asymmetrical over prairie and pasture surfaces. They pointed out that morning dew on plant canopy caused an asymmetrical albedo. Wen et al. (2009) found similar results in arid oases of China. Figure 6 shows a time series of the difference between air temperature and dew point temperature (ΔT) during the growing season of spring wheat. Data were collected at 2 m above the surface. It seems that it was relatively unsuitable for dew formation. However, the crop height never exceeded 1 m, suggesting that the difference between air temperature and dew point temperature in the nighttime at the interface of plant canopy to air would be much closer to 0° than at 2 m. Moreover, the air temperature difference between daytime and nighttime was pronounced (Fig. 7) and the wind speed in the nighttime was weak (Fig. 5), which would easily cause dew formation on the plant leaves under the radiative cooling of surface and the increasing dropping of air temperature (Pinter 1986). Unfortunately, no measurements on dew at spring wheat leaf surface were made in the present study. However, Pan et al. (2010) found that dew formation and water adsorption began to occur on the surface of biological soil crusts 200 m from the spring wheat field when the relative humidity was greater than 40 % at 2 m height. Our meteorological data showed that the relative humidity at 2 m was higher than 40 % in the 25 % of the time in 1 day. Finally, spring wheat canopy enabled a high water vapor from soil below the canopy, which is also an important factor for dew formation (Pinter 1986; Jacobs et al. 1994; Agam and Berliner 2006). Additionally, dew droplets on the leaf surface of spring wheat was seen in the morning during field observations. Based on the above arguments, we thus assumed dew formation on the leaf surface of spring wheat.

In conclusion, by analyzing three main possible causative factors, i.e., surface soil moisture, wind and dew, and the meteorological data together with in situ observations, we inferred, according to the existing studies (Minnis et al. 1997; Wen et al. 2009; Pan et al. 2010) and our present results, that diurnal albedo asymmetry is cuased mainly by early morning dew on the leaf surface. As the dew evaporates, the diurnal variation of surface albedo became symmetrical (Figs. 3, 4).

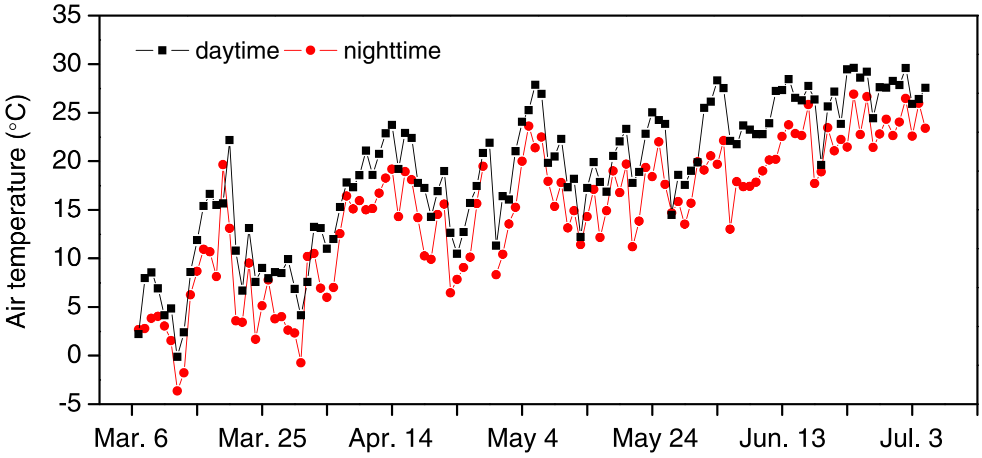


Fig. 7 Comparison of daytime and nighttime air temperature during the growth period of spring wheat. Daytime air temperature here refers to the average value from 7:00 to 19:00 and nighttime air temperature refers to the average value from 19:00 to 7:00 the next morning

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