Surface radiation characteristics of the Ali area, Northern Tibetan Plateau

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Abstract

This study analyses the diurnal seasonal mean and the seasonal and annual variation in the radiation budget at the Ali Meteorological Bureau observation station in the northern Tibetan Plateau for 2019. The results indicate that the daily average variation in incidental shortwave and reflected radiation across all seasons in the Ali area had typical unimodal symmetry. The average daily variation in incidental shortwave radiation was in phase with reflected radiation, but the amplitude of the incidental shortwave radiation was greater than that of reflected radiation. The daily amplitude, daily average, and monthly average upwelling longwave radiation were greater than those for downwelling radiation, and the diurnal cycle of downwelling atmospheric radiation lagged behind that of upwelling longwave radiation. The daily amplitude of surface net radiation in winter in the Ali area was less than in other seasons, as expected, and the seasonal transformation had a great impact on the net radiation for this region. The net radiative energy at the surface was highest in late spring and early summer, which played a decisive role in the formation of terrestrial and atmospheric heating.

1. Introduction

The surface energy budget and radiation balances are important in the context of land surface processes and land-atmosphere interaction (Jian and Qiang 2012), as well as the water cycle. These topics have been widely studied since the mid-20th century, with observations and experiments involving different underlying surfaces. Outside of China, this work has focused on forests, farmland, and grasslands in semi-arid areas (Moore 1976, Visvanadham and Dos 1990); within China, the relevant work has mainly been carried out in the Qinghai Tibetan Plateau and the northwest arid region (Hui et al. 1999, Yuanfa et al. 2005, Rongsheng and Yaoming 2010). The research in China has made great progress in clarifying the energy budget (Guoliang et al. 1995, Zeyu et al. 2005), radiation balance and its components (Yurong and Guodong 1983, Shiqiang et al. 2005), heat source intensity (Yurong and Guodong 1983, Zhibao et al. 1987, Zeyu et al. 2005), and physical processes in land-atmosphere interaction (Xiangde and Liangshou 2006).

However, most studies of the surface radiation balance over the Tibetan Plateau are based on short-term or local observations (Ren et al. 1997, Dahlback et al. 2007), especially in the northern Tibetan Plateau, where environmental conditions make it difficult to collect measurements. Relevant studies focus mainly on the Naqu area of the northern Tibetan Plateau (Numaguti et al. 1999), where the observation data are relatively long-term (Yuanfa et al. 2005, Rongsheng and Yaoming 2010). Therefore, more research needs to be conducted in the Ali area of the northern Tibetan Plateau.

We use observation data from the ‘land-atmosphere interaction’ observation station at the Ali Meteorological Bureau in the northern Tibetan Plateau to analyse the variation in each component of the radiation budget for 2019. The results are intended to provide data to support the parameterisation of land surface processes and research into land-atmosphere interactions in the northern Tibetan Plateau.
2. Materials and methods

2.1. Study area
The northern Tibetan Plateau is located in the hinterland of the Qinghai Tibet Plateau, it is bordered by the Gangdise-Tanggula mountains to the south, the Karakorum-Hoh Xil mountains to the north, a watershed of internal and external water systems to the east, and Gongzhuko-Geji-Duoma to the west. The northern Tibetan Plateau has an average altitude of 4800 m, an annual average temperature usually below 0 °C, and annual average precipitation ranging from 50–300 mm, more than 80% of which occurs between June and September. The annual sunshine duration is 2800–3400 h. The region covers a total area of 597,000 km², and makes up 1/4 of the total area of the Tibetan Plateau. Administratively, it is under the jurisdiction of the Naqu and Ali regions of the Tibetan Plateau.

2.2. Data
The Shiquanhe land-atmosphere interaction observation station (built by Institute of Plateau Meteorology, China Meteorological Administration, Chengdu) is located at the meteorological observation field (32.49 °N, 80.10 °E) of the Ali Prefecture Meteorological Bureau in Tibet. The station is at an altitude of 4271 m and has an annual average temperature of 0.2 °C, annual average precipitation of 60–70 mm, and an underlying surface of sandy soil. There is no vegetation cover at any time of year, and the ground surface of the test site is flat and open. The station collects gradient observation measurements of wind, temperature, and humidity, as well as measurements of fluxes, radiation, and soil temperature and water content.

The radiation data used in this study mainly come from a four-component radiometer measuring upwelling and downwelling shortwave and longwave radiation, from which net radiation can be estimated. A Kipp & Zonen CM11 pyranometer is installed 1.5 m above the ground, facing the underlying surface. Incident and reflected radiation are measured within 305–2800 nm, and the total measurement band including longwave radiation is 305–50,000 nm. We averaged the observations conditionally for various weather conditions. We used Beijing time to define days starting at 00:00; spring is defined as March to May; summer is June to August; autumn is September to November; and winter is January, February, and December of the same year. The observation data period was the whole of 2019, and we used 30 min averaged values. For missing data, we used the average of the values from the two preceding days and the two following days. Finally, we calculated the diurnal seasonal mean and the seasonal and annual variation for each radiation budget component.

3. Results and discussion

3.1. Relationship between surface radiation components
The incidental shortwave radiation at the surface is defined as the solar radiation that reaches the ground following absorption and scattering by the atmosphere and reflection and attenuation by clouds. The component of total shortwave radiation reflected by the ground surface is called reflected radiation. The ground emits longwave radiation to the atmosphere, and the atmosphere also reflects the longwave radiation downward. According to radiation balance theory, in the boundary layer, the net radiation, Rn, can be calculated by the following formula:

\[ R_n = (SW_l - SW_u) + (LW_l - LW_u), \]  

where \( SW_l \) is downwelling shortwave radiation (incidental), \( SW_u \) is upwelling shortwave radiation (reflected), \( LW_l \) is downwelling longwave radiation (atmospheric), and \( LW_u \) is upwelling longwave radiation (surface); the unit of measurement is \( \text{W} \cdot \text{m}^{-2} \).

3.2. Shortwave radiation
Shortwave radiation is composed of total incident radiation and reflected radiation. Daily incident shortwave radiation depends upon solar elevation, cloudiness, and length of day (Ren et al 2012), while reflected radiation is closely related to surface properties, in addition to the influence of latitude and sky conditions.

Figure 1 presents the average daily variation in shortwave radiation for different seasons in the Ali region. This is characterised by a typical single peak having symmetry, starting to increase at approximately 09:00, reaching a maximum value at about 15:00, and then decreasing gradually and reaching zero at approximately 21:00. Between 10:00 and 15:00, apart from at 14:00, the incidental shortwave radiation was greater in spring than in summer. A similar situation occurs in the eastern region of the Qinghai Tibetan Plateau (Wanfu et al 2013), and this may be related to the seasonal difference in total cloud amount; a larger total cloud amount will locally reduce the incidental shortwave radiation (Jian and Qiang 2012). The average daily variation in reflected
radiation was in phase with the incidental shortwave radiation, indicating that for the Ali region, the reflected radiation is directly influenced by the incidental shortwave radiation.

In the Ali region, the maximum average daily shortwave radiation for spring (982.12 W·m⁻²) and summer (972.25 W·m⁻²) differed minimally, and the values for autumn and winter were 810.93 W·m⁻² and 656.10 W·m⁻², respectively. During spring, the maximum daily variation in incidental shortwave radiation was greater in the Ali region was greater than that in the Gaize region (930 W·m⁻²) (Yuanfa et al. 2005) and wetlands in the northern Tibetan Plateau (909.36 W·m⁻²) (Huigen et al. 2010).

No significant difference was observed in the average daily variation in reflected radiation between spring and winter in the Ali region. The maximum average daily variation in reflected radiation in spring was 199.54 W·m⁻², which was less than that in the Gaize area (252 W·m⁻²) (Yuanfa et al. 2005). The values for winter, summer, and autumn were 191.23 W·m⁻², 181.74 W·m⁻², and 156.33 W·m⁻², respectively. The maximum difference between the seasonal average daily variation in reflected radiation between spring and autumn was 43.21 W·m⁻², differing significantly from that in the northern Tibetan Plateau wetlands (Huigen et al. 2010).

Figure 2 presents the variation in daily and monthly shortwave radiation in the Ali region. The daily and monthly averages (excluding data affected by snowfall) of incidental and reflected radiation first increased and then decreased, but the amplitude of the change was greater for incidental shortwave radiation than for reflected radiation. With the gradual increase in solar elevation, the incidental shortwave radiation increased rapidly (figure 2(b)) and reached its peak (351.23 W·m⁻²) in June, which is one month earlier than the peak observed in the Wudaoliang area (Guoliang et al. 1995).

The Tibetan Plateau is affected by the rainy season in July and August, including the southwest monsoon (Duming and Jianyun 1993). Cloud cover increases during this time, resulting a large decrease in daily mean incidental shortwave radiation in July and August. The trend in incidental shortwave radiation is mainly affected by atmospheric circulation and climate (Yurong and Guodong 1983), similar to conditions in the wetlands in the northern Tibetan Plateau (Huigen et al. 2010). The phase of annual variation in reflected radiation was the same as that of incidental shortwave radiation.

Due to the rapid increase of incidental shortwave radiation, the reflected radiation was at a maximum in June. With the arrival of the monsoon, the soil gradually became wet, therefore gradually decreasing the reflected radiation. In July, the reflected radiation decreased significantly with the rapid decrease in incidental shortwave radiation.
radiation. The minimum value was observed in August. At the end of the rainy season, the surface albedo increased, and a second peak appeared in September.

The annual average incidental shortwave radiation for the Ali region in 2019 was 255.96 W·m⁻²; this value is higher than the previously measured value of 252.7 W·m⁻² (Duming and Jianyun 1993). The average incidental shortwave radiation in spring, summer, autumn, and winter was 308.64 W·m⁻², 308.43 W·m⁻², 233.39 W·m⁻², and 171.30 W·m⁻², respectively. The sharp increase in solar radiation during the spring likely caused an increase in ground heating, thereby affecting seasonal transition of mean pressure systems in the planetary boundary layer (Guoliang et al 1995). The annual average reflected radiation in the Ali region in 2019 was 56.95 W·m⁻², and the average incidental shortwave radiation in spring, summer, autumn, and winter was 84.42 W·m⁻², 60.75 W·m⁻², 48.42 W·m⁻², and 52.56 W·m⁻², respectively. The maximum daily reflected radiation (158.45 W·m⁻²) was observed on 26 January 2019, and the minimum value (17.35 W·m⁻²) was observed on 13 December 2019.

### 3.3. Longwave radiation

Net longwave radiation at the surface is made of up two components: longwave radiation emitted from the ground to the atmosphere (upwelling longwave radiation) and longwave radiation emitted by the atmosphere (downwelling atmospheric radiation). These are two of the four components of the net radiation balance (equation (1)), and can be a ground heat source or sink (Yuanfa et al 2005). Upwelling longwave radiation is mainly determined by the surface temperature, and atmospheric radiation is closely related to the air temperature and the water vapour content in the atmosphere (Lingen et al 2001).

Figure 3 presents the average daily variation in longwave radiation for different seasons in the Ali region. This is characterised by a typical single peak having symmetry, and the amplitude and magnitude of the daily variation in upwelling longwave radiation were greater than those for downwelling atmospheric radiation. As shown in figure 3(a), upwelling longwave radiation in the Ali area during different seasons increased rapidly with sunrise, reached a maximum value at approximately 15:00, and then decreased gradually. The reason for this is that upwelling longwave radiation is mainly determined by surface temperature, and surface temperature increases with the increase in incidental shortwave radiation. The incidental shortwave radiation reaching the ground in the Ali region started to increase at about 09:00, resulting in the same trend in upwelling longwave radiation after 09:00. Due to the close relationship between downwelling atmospheric radiation and air temperature, and because changes in air temperature lag behind the surface temperature, the average daily variation in downwelling atmospheric radiation lags behind the upwelling longwave radiation. The amplitude of the daily variation in downwelling atmospheric radiation was only 1/4 that of upwelling longwave radiation. A similar situation was also observed in the Nyingchi area of the Qinghai Tibetan Plateau (Xinying et al 2015).

The maximum daily variation in upwelling longwave radiation in the Ali region was 526.49 W·m⁻² in summer, 477.44 W·m⁻² in spring, 462.66 W·m⁻² in autumn, and 346.58 W·m⁻² in winter. The maximum difference between the seasonal averages of daily variation in surface radiation was 179.91 W·m⁻², which was less than in the Gaize area (195.5 W·m⁻²) (Yuanfa et al 2005), but greater than in the wetlands in the northern Tibetan Plateau (84.42 W·m⁻²) (Huigen et al 2010). We observed a seasonal variation in downwelling atmospheric radiation, but it was very small, ranging from 150 W·m⁻² to 350 W·m⁻². The maximum value was 304.07 W·m⁻²; this occurred in summer when there was more cloud cover, and the minimum value was 193.11 W·m⁻², during winter. Downwelling longwave radiation was relatively stable in winter and summer, but it was more variable in spring and autumn due to circulation being in the transition stage (Rongsheng and Yaoming 2010).

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**Figure 3.** Average daily variation in longwave radiation for different seasons in the Ali region ((A): upwelling longwave radiation; (B): downwelling longwave radiation).
Figure 4 presents the variation in daily and monthly longwave radiation in the Ali area. The daily and monthly values of longwave radiation first increased and then decreased, but the daily and monthly values of upwelling longwave radiation were greater than the downwelling atmospheric radiation for the same period. With the gradual increase in solar elevation in July, the upwelling longwave radiation reached its peak value (421.60 W·m$^{-2}$; figure 4(b)), one month later than the peak value for incidental shortwave radiation, while downwelling atmospheric radiation reached its peak value (309.60 W·m$^{-2}$) in August.

The average upwelling longwave radiation in spring, summer, autumn, and winter in the Ali region was 356.91 W·m$^{-2}$, 417.49 W·m$^{-2}$, 358.65 W·m$^{-2}$ and 272.44 W·m$^{-2}$, respectively. The maximum daily upwelling longwave radiation (454.90 W·m$^{-2}$) occurred on 7 July 2019, and the minimum value (207.60 W·m$^{-2}$) occurred on 29 January 2019. The maximum annual variation was 247.3 W·m$^{-2}$, and the annual average value was 351.79 W·m$^{-2}$, indicating large seasonal and annual variations in upwelling longwave radiation, and the annual longwave radiation from the ground is also very large.

Values for downwelling atmospheric radiation in the Ali region were the largest in summer, slightly larger in autumn than in spring, and smallest in winter. The average downwelling atmospheric radiation in spring, summer, autumn, and winter were 212.15 W·m$^{-2}$, 290.91 W·m$^{-2}$, 224.82 W·m$^{-2}$, and 177.48 W·m$^{-2}$, respectively. The seasonal difference was 113.43 W·m$^{-2}$, with an average annual value of 226.61 W·m$^{-2}$.

These results indicate that downwelling atmospheric radiation varies greatly in winter and summer, and the annual variation and total amount are also large.

3.4. Net radiation

Net radiation at the surface, Rn, is defined by equation (1), and its magnitude and variability are simultaneously controlled by each component. The most important factors are the solar elevation and total cloud cover. Figure 5 presents the variation in net radiation for the Ali region. The average diurnal variation of surface net radiation for all seasons exhibits a typical single peak having a symmetrical diurnal variation; the amplitude in winter was smaller than in other seasons, as expected. The transition from negative to positive net radiation lagged behind the incidental shortwave radiation, while the transition from positive to negative occurred earlier than for the incidental shortwave radiation.

The average daily variation in net radiation was the largest in summer, followed by spring, autumn, and then winter, which indicates that the seasonal variation in net radiation is mainly influenced by the seasonal variation in incidental solar radiation (Yaoming et al 1997). The maximum daily variation in surface net radiation in
summer was 563.87 W m$^{-2}$, which is larger than in the Gaize area (443.2 W m$^{-2}$) (Yuanfa et al 2005), and is similar to the value for the wetlands in the northern Tibetan Plateau (563.10 W m$^{-2}$) (Huigen et al 2010). In winter, the maximum daily variation in net radiation was 313.64 W m$^{-2}$, which is greater than in the Gaize area (256.9 W m$^{-2}$) (Yuanfa et al 2005), but less than that for the wetlands in the northern Tibetan Plateau (360.78 W m$^{-2}$) (Huigen et al 2010).

The change in daily net radiation in the Ali region was consistent with that of incidental shortwave radiation morphology, which tends to increase first and then decrease. The annual average surface net radiation was 73.84 W m$^{-2}$, and the average values for spring, summer, autumn, and winter are 98.02 W m$^{-2}$, 121.10 W m$^{-2}$, 51.14 W m$^{-2}$, and 23.77 W m$^{-2}$, respectively. The maximum surface net radiation (174.98 W m$^{-2}$) occurred on 12 August 2019, and the minimum surface net radiation (−18.61 W m$^{-2}$) occurred on 24 January 2019. The annual variation in net radiation is closely related to the atmospheric circulation and climate. The seasonal variation in net radiation was large, and the net radiation in summer was 5.10 times that in winter, highlighting the influence of seasonal change on net radiation. The net radiation was largest at the end of spring and the beginning of summer, when the net energy obtained by the surface was greatest.

4. Discussion

The Tibetan Plateau has an important influence on the weather and climate of China and even East Asia. The study of the process of land-atmosphere interaction over the plateau is one of the key and difficult problems to reveal its influence. The surface energy budget and radiation balances are important in the context of land surface processes and land-atmosphere interaction, and also the main links of land surface energy, water conversion and circulation.

The components of radiation budget of Ali area are very important for regional energy and water balance, but the Ali area is sparsely covered by observations. We have made field observations for several years, but the missing rates of observation data were high in the early stage, and only the observation data in 2019 was relatively complete, so this study analyses the components of the surface radiation budget in 2019. Due to the lack of reference on surface radiation budget in Ali area, it is impossible to judge the interannual variability in the components of radiation budget. In the future, we will interpolate the missing data, and analyze the interannual variability in the components of radiation budget in the Tibetan Plateau.

5. Summary and conclusions

We analysed the diurnal seasonal mean and the seasonal and annual variability of each component of the radiation budget using observation data from a land-atmosphere interaction station at the Ali Meteorological Bureau in the northern Tibetan Plateau, for 2019. Our conclusions are as follows:

1. The average daily variation in incidental shortwave radiation and reflected radiation for all seasons typically had unimodal symmetry, and the change in reflected radiation was in phase with total radiation. The maximum values of average daily variation in incidental shortwave radiation did not differ significantly between spring and summer (982.12 W m$^{-2}$ and 972.25 W m$^{-2}$, respectively). The values in autumn and winter were 810.93 W m$^{-2}$ and 656.10 W m$^{-2}$, respectively. The maximum average daily variations in reflected radiation were 199.54 W m$^{-2}$ in spring, 191.23 W m$^{-2}$ in winter, 181.74 W m$^{-2}$ in summer, and 156.33 W m$^{-2}$ in autumn. The maximum difference in seasonal averages of the daily variation in reflected radiation was 43.21 W m$^{-2}$, mainly in spring and autumn, which is quite different from that in the northern Tibetan Plateau wetlands.

2. The daily and monthly values of incidental shortwave and reflected radiation exhibited a similar trend, first increasing and then decreasing. The seasonal variation in incidental shortwave radiation was mainly affected by the atmospheric circulation and climate, but the amplitude was greater than for reflected radiation, as expected. The annual average incidental shortwave radiation in 2019 was 255.96 W m$^{-2}$, and the averages for spring, summer, autumn, and winter were 308.64 W m$^{-2}$, 308.43 W m$^{-2}$, 233.39 W m$^{-2}$, and 171.30 W m$^{-2}$, respectively. The annual average reflected radiation was 56.95 W m$^{-2}$, and the averages for spring, summer, autumn, and winter were 65.87 W m$^{-2}$, 60.75 W m$^{-2}$, 48.42 W m$^{-2}$, and 52.56 W m$^{-2}$, respectively.

3. The amplitude and magnitude in daily variation of upwelling longwave radiation were greater than those of downwelling atmospheric radiation, and the average daily variation in downwelling atmospheric radiation lagged behind the upwelling longwave radiation. The maximum daily variation in upwelling longwave radiation was 526.49 W m$^{-2}$ in summer, 477.44 W m$^{-2}$ in spring, 462.66 W m$^{-2}$ in autumn, and
346.58 W · m⁻² in winter. The difference between the seasonal maxima of the average daily variation in downwelling atmospheric radiation was very small. The maximum of these (304.07 W · m⁻²) occurred in summer, and the minimum (193.11 W · m⁻²) occurred in winter.

4. The daily and monthly mean values of upwelling longwave radiation were greater than the downwelling atmospheric radiation values for the same period. The average surface radiation in spring, summer, autumn, and winter in the Ali region was 356.91 W · m⁻², 417.49 W · m⁻², 358.65 W · m⁻², and 272.44 W · m⁻², respectively, with an annual variability of 247.3 W · m⁻² and annual average of 351.79 W · m⁻². These results indicate that the seasonal and annual variations in upwelling longwave radiation are large, and the annual total amount of longwave radiation from the ground is also large. The average downwelling atmospheric radiation in spring, summer, autumn, and winter were 212.15 W · m⁻², 290.91 W · m⁻², 224.82 W · m⁻², and 177.48 W · m⁻², respectively. The seasonal difference was 113.43 W · m⁻², with an average annual value of 226.61 W · m⁻². These results indicate that the downwelling atmospheric radiation varied greatly in winter and summer, and the annual variation and total amount were also large.

5. The amplitude of daily variation in net radiation for the Ali region in winter was less than that for other seasons, as expected. The average daily variation in net radiation was largest in summer and smallest in winter, indicating that it is influenced by seasonal variations in incident solar radiation. The annual net radiation was 73.84 W · m⁻², and the averages for spring, summer, autumn, and winter were 98.02 W · m⁻², 121.10 W · m⁻², 51.14 W · m⁻², and 23.77 W · m⁻², respectively. The seasonal variation in net radiation for the Ali region was large, and the net radiation in summer was 5.10 times that in winter, highlighting the influence of seasonal change on net radiation. The net radiation was largest at the end of spring and the beginning of summer, when the net energy at the surface was greatest.

Data availability statement
The data that support the findings of this study are available upon reasonable request from the authors.

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