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Analyses of temperature and humidity profiles and heat balance of the surface boundary-layer in the hinterland of the Taklimakan Desert

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The daily variation regularities of micro-meteorological features, such as the surface layer temperature and humidity profiles of the inner desert in summer, the temperature of sand bed, the radiation of the earth's surface and the heat balance, were analyzed by combination method and logarithm regression according to the data obtained from the Atmospheric Environmental Observation Station of Taklimakan Desert in July—August of 2006 and 2007. It has been shown that temperature inversion occurred near the surface layer at night in summer, the temperature increased with the height within a certain altitude range, and the reverse was true during the daytime. The ground surface radiation balance of the Taklimakan Desert was mainly positive; other radiation components (the global radiation, the reflective radiation, the ground upward long wave radiation and the net radiation) exhibited daily variation characteristics evidently and showed normal diurnal cycle, except for the downward atmospheric long-wave radiation. The heat exchange of the surface layer of the desert was dominated by turbulence sensible heat, and only a small portion of heat was transferred to the atmospheric surface layer in the form of latent heat. The surface sensible heat and latent heat changed with the increase and decrease of sun elevation angle, with maximum of the latent heat appearing in wee hours and the peak value of the sensible heat appearing at noon. Observation and analysis showed that heating effect of the underlying surface of the desert was great on the aerosphere; the surface was a high heat source during the day and became a weak cold source at night.

Taklimakan Desert, temperature profile, humidity profile, radiation balance, heat balance

With the whole earth as an object, the global change researches have become the frontier research field of contemporary world science due to the climate warming and deterioration of human living environment[1]. From the middle of 1980s, with the coordination of WCRP and IGBP, more than 50 land surface process experiments have been carried out in the main representative climatic and ecological regions around the globe. At present, the observation of land-air interaction and the researches on its influence on monsoon and climate have become the key contents of Climate Variability and Predictability Programme (CLIVAR)[2]. Since the late 1980s, research projects, such as Heihe Region Land-Atmosphere Interaction Observation Experiment Study (HEIFE), Study on Inner Mongolia Semi-arid Grassland Soil-Vegetation-Atmosphere Interaction (IMGRASS), the Second Tibetan Plateau Atmospheric Experiment (TIPEX), Land-atmosphere Interaction Experiment in Arid Region of Northwest China (NWC—ALIEX) and Asian Monsoon Experiment-Tibetan Plateau Experiment (GAME—Tibet), etc., have been launched successively

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in China and a series of important research results have been achieved. The bulk transfer coefficients of the Heihe Desert and the Gobi Area were studied first by Zuo and Hu[3]; the turbulent transport and bulk transfer coefficients of the Tibetan Plateau area were studied by Bian et al.[4], Li[5−7], Liu[8] and Qian et al.[9] respectively; the changes of the surface feature and the interaction of climate of the Inner Mongolia Grassland were calculated and analyzed by Lü et al.[10]; the momentum transfer coefficients and sensible heat bulk transfer coefficients of Dunhuang Gobi were studied by Zhang et al.[11]; the characteristics of land surface of the Loess Plateau were studied by Wei et al.[2] and Wang et al.[12] respectively. However, researches on land-air interaction and surface energy balance of the Taklimakan Desert, the largest drifting desert of China, are rare.

Located at the Eurasia hinterland of middle latitude Northern Hemisphere, the Taklimakan Desert, the largest drifting desert of China, the second largest in the world, is in the centre of the Tarim Basin, Xinjiang, its average elevation is above 1000 m, with an area of 33.76×10^4 square kilometers. The mean annual precipitation of this area is less than 40 mm, wind sand disasters occur frequently, belonging to a typical extreme arid climate area.

Many researches on the weather and climate of the Taklimakan Desert have been done by scholars around the world, especially by those from China[13−24]. In the 1980s, an investigation team of Taklamakan Desert launched a four-year investigation on this region and accumulated massive precious meteorological data. A large number of distinctive new viewpoints and new conclusions were formed by the application of many theories and methods[13]. However, some fundamental scientific problems,such as surface radiation of the desert, heat balance, atmospheric structure of the surface layer, surface heat source intensity and bulk transfer coefficients have not been fully studied due to the scarcity of weather stations in the desert area, the limitation of observational means and data and some important physical processes of the desert surface, such as the scarcity of detailed and continuous observation of surface energy balance. The observation and experiment station of the Taklimakan Desert was set up by Urumqi Desert Meteorological Research Institute of China Meteorological Administration, and an 80 m iron tower with gradient flux and radiation observation system was deployed to carry out continuous observation on the atmospheric boundary layer of the desert in 2003. Based on this, this paper made use of the micrometeorology observation data obtained in July-August of 2006 and 2007 to make deep analysis of temperature and humidity structure and surface energy balance character of the surface boundary layer of the inner desert, which would promote the cognition of land surface process of the arid desert area and lay a good foundation for the further discussion on the atmospheric physical process of the boundary layer of the desert and the defense and treatment of natural disaster like sandstorm, etc.

1 Test site, observation instruments and data

The gradient data of wind, temperature and humidity, ground temperature data and radiation and heat data, which were obtained from the Atmospheric Environmental Observation Station of Taklimakan Desert in July—August of 2006 and 2007, were used in this study. The geographic location of this station is at 39°00′N, 83°40′E, the elevation is 1099.3 m. The observing site was open all around, the surface of which was drifting desert formed by sand dunes. There were a few desert bush plants in the living area near the experimental site. The characteristics of the underlying surface of the experimental site basically represented the surface features of the Taklimakan Desert. The iron tower system was composed of ten gradient observation platforms, the height of which was 0.5, 1, 2, 4, 10, 20, 32, 47, 63, 80 m respectively. All the detection instruments used were equipped with the state-of-the-art detecting sensors, wind speed, wind direction, temperature and humidity sensor produced by VAISALA from Finland; the model numbers were WAA151, WAV151, QMH102 (HMP45D), QMH102 (HMP45D) respectively. The instantaneous data sampling frequency of wind, temperature and humidity was one group per 10 s. The minute data were obtained by averaging the 6 groups of instantaneous data of every minute; the hourly statistical data were obtained through averaging the 60 groups of minute data of every hour. The natural solar radiation components included the global radiation, direct radiation,reflective radiation, the atmospheric downward long wave radiation and the ground upward long wave radiation. They were installed on a 1.5 m observation shelf. The radiation instruments were produced by Kipp &

Zone from Holland, the model numbers were CM21 and CG4. The heat flux plates were installed at the depths of 1, 10, 20, 40, 80, 160 cm in the soil, and the model number was HFP01SC. The soil heat flux of 1 cm was employed to do the calculation. There were five layers of sand bed temperature, the depths of which were 0, 5, 10, 20 and 40 cm.

2 Calculation methods

2.1 Combination method

Combination method[3,11,25] is an indirect method to calculate the surface turbulent fluxes by the combination of the gradient data of wind, temperature, humidity, surface natural solar radiations and soil heat flux. This paper employed the combination method to get the results of sensible heat flux H and latent heat flux λE by using the gradient data of wind, temperature, humidity, surface natural solar radiations and soil heat flux obtained from the micrometeorology tower on August 13—31, 2006. The concrete calculation process is as follows:

According to the gradient data of wind, temperature and humidity, the sensible heat flux H_0 and latent heat flux λE_0 without stratification correction can be calculated first,

$$H_0 = -\rho C_P k^2 Z_A^2 \frac{\partial u}{\partial z}\frac{\partial \theta}{\partial z}, \tag{1}$$

$$\lambda E_0 = -\rho \lambda k^2 {Z_A}^2 \frac{\partial u}{\partial z}\frac{\partial q}{\partial z}, \tag{2}$$

where k is Karman constant, $k=0.40$; C_P is the specific heat at constant pressure of air; λ is the latent heat of vaporization of water; Z_A is the geometric mean of the heights of the two observation platforms, Z_i and Z_{i+1}, $Z_A=\sqrt{Z_i Z_{i+1}}$. Others are general symbols, where potential temperature θ and q could be expressed as

$$\theta = T\left(\frac{1000}{P}\right)^{0.286}, \qquad q = 0.622\frac{e}{P}.$$

The approximate difference of the surface net radiation and soil heat flux is defined as surface available energy A:

$$A = R_n - G_0, \tag{3}$$

where R_n is net radiation, which can be obtained by the calculation of the observation data of the components of radiation balance; G_0 is the soil heat flux of 1 cm.

$$A=H+\lambda E, \tag{4}$$

Introduce the influence function of stratification:

$$F = \frac{A}{H_0 + \lambda E_0}. \tag{5}$$

The calculation formula of surface sensible heat flux H and latent heat flux λE is obtained when the surface energy balance, heat and the influence function of stratification of moisture are the same:

$$H=H_0 F, \tag{6}$$

$$\lambda E=\lambda E_0 F. \tag{7}$$

Surface available energy A can be obtained by eq. (3) using the data of soil heat flux and net radiation. The sensible heat flux H_0 and latent heat flux λE_0 without stratification correction can be calculated by eqs. (1) and (2) using the gradient observation data of wind, temperature, humidity. The influence function of stratification can be gained by eq. (5) and finally heat flux H and latent heat flux λE can be gained by eqs. (6) and (7).

2.2 Arithmetic mean and logarithm regression analysis

In this study, the arithmetic mean method was employed to calculate the monthly average temperature, ground temperature and monthly average specific humidity of each gradient at every moment, and then to calculate the monthly average temperature during day and night (Here, 20:00—08:00 was used as night, 08:00—20:00 as daytime). The temperature profile was given within the height of 80 m, the temperature variation with the height was analyzed by logarithms regression analysis method and the relationship between the turbulent sensible heat exchange of the surface layer of inner desert and temperature was discussed.

3 Analyses of results

3.1 The characteristics of the temperature profile of the 80 m iron tower

The average temperature profile is given in Figure 1, which was at the height of 80 m of the inner Taklimakan Desert in July-August of 2006 and 2007. Table 1 shows that the temperature profile possessed distinct diurnal variation characteristics, the regularity of which was divided into two phases: the temperature decreased with the height in day time (insolation type) and increased with the height at night (radiation type). The time when the temperature decreased with the height occurred approximately at 09:00—10:00 am after sunrise in the early morning. The time when the temperature increased with the height occurred approximately at 20:00—21:00 pm after sunset. The ground surface was heated by the solar radiation during the day and conveyed the heat to the air layer near the ground in the form of sensible heat turbulent exchange , leading to the rising of the temperature of the surface layer. The nearer the air layer to the ground, the more heat it could get, the higher the temperature, and *vice versa*. Thus, the vertical distribution of the air temperature declined with height. The ground radiation decreased at night, the heat was transferred from the atmosphere to the sand surface ,thus the ground temperature was lowered. The nearer the air layer to the ground, the more it could be influenced by the surface, the lower the temperature could be, and *vice versa*. Therefore, the temperature inversion happened from the ground, and the temperature vertical distribution was opposite to the solar type.

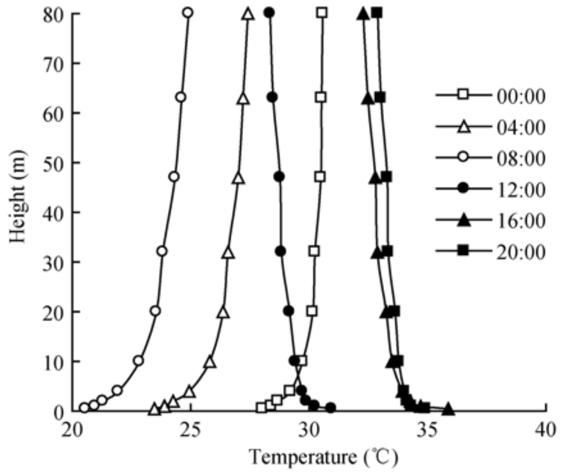

Figure 1 The average temperature profiles of July-August of 2006 and 2007.

The average temperature profile of nighttime and daytime is given in Figure 2, which was at the height of 80 m of the Atmospheric Environment Observation Station of Taklimakan Desert in July-August of 2006 and 2007. It can be clearly seen from Figure 2 that the average night temperature profile of these two months was opposite to the one of daytime. The night temperature increased with the height, presenting temperature inversion phenomenon; the daytime temperature decreased with the height. At the height of 20 m near the ground, the average temperature gradient varied greatly at night, the ascending rate of night temperature reached 11.4℃/100 m in August and 7.5℃/100 m in July, the average temperature gradient descended gradually above 20 m. Regression analysis has been used in this study to analyze the night temperature profile in July and August, and it is found that the logarithmic function fits the actual situation well, and the regression equation is

$$Y = b_0 + b_1 \ln x.$$

The temperature logarithmic function regression equation of July is

$$Y = 27.084 + 0.383 \ln x,$$

where Y is a dependent variable, standing for temperature; x is independent variable, for height. The total variance explained of this is 99.0%, F-test value is 798.75, reaching the significance level of 0.001.

The temperature logarithmic function regression equation of August is

$$Y = 27.391 + 0.599 \ln x.$$

The total variance explained of this is 99.4%, F-test value is 1276.64, reaching the significance level of 0.001 too.

Previous research indicated that the highest temperature appeared in July in the Taklimakan Desert. However, the observation data from 80 m iron tower of the Atmospheric Environment Observation Station of Taklimakan Desert (Figure 2) shows that the average temperature of every gradient during daytime and nighttime in August was higher than that in July.

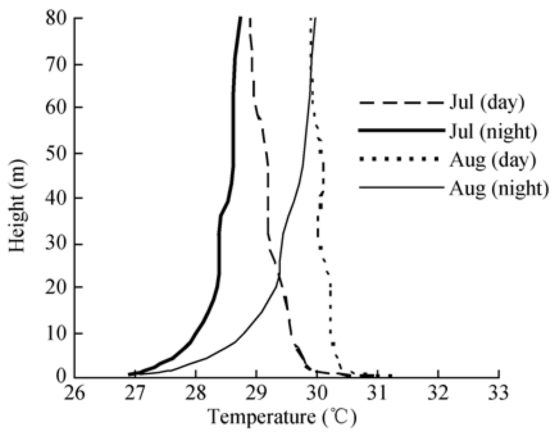

Figure 2 The average temperature profiles during the daytime and nighttime.

3.2 The temperature profiles characteristics of the sand layer

The diurnal variation process of the ground temperature is drawn according to the observation data from the Atmospheric Environment Observation Station of Taklimakan Desert (Figure 3). It was indicated that the sand layer displayed diurnal variation evidently; the charac-

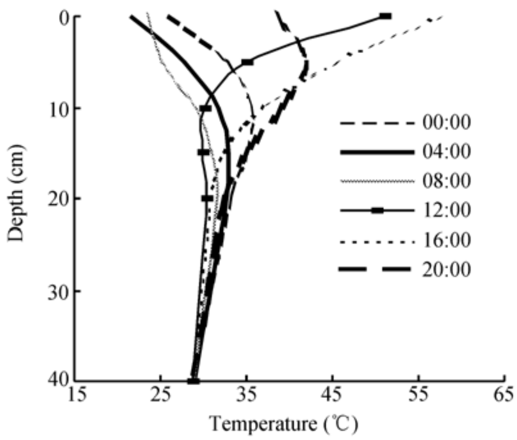

Figure 3 The average sand layer temperature profiles of July, 2006 and 2007.

teristics of 0 and 5 cm were most distinct. The phase and amplitude changed with the depth. The diurnal variation of 40 cm was no longer evident, which showed slight difference with the ground temperature of Gurbantunggut Desert[26]. During the diurnal variation of the sand layer temperature, the peak value of 5 cm sand layer occurred at around 15:00—16:00 pm, the minimum at around 07:00 am. The time of peak value delayed with the depth increasing. The vertical gradient of temperature decreased with the depth. When the ground gained lots of radiant energy during the daytime, the ground temperature went up sharply, the heat was transferred from the top to bottom, meanwhile, the vertical distribution of temperature decreased downward. When the ground temperature went down at night, the situation was opposite, namely, the sand layer temperature increased with the depth, the direction of the heat flux pointed to the ground. During the variation of the sand layer temperature, the fluctuation of rate and depth changed according to the maximum and minimum critical value of the day. The downward regression rate reached its maximum at the highest temperature, the regression depth of the sand layer was the deepest. The upward progressive rate reached its maximum at the lowest temperature, the progressive depth of the sand layer was the deepest. As shown in the vertical temperature profiles of the sand layer (Figure 3), heat energy was redistributed in the sand layer constantly due to the change and transfer of heat with time. Observation showed that the zero layer of the heat transfer was at 20 cm, when the surface sensible heat flux reached the highest in the Taklimakan Desert. According to the comparison of the sand layer temperature profiles among the Taklimakan Desert, Gurbantunggut Desert and Naiman Desert[26], there were some identities in the changes of the sand layer temperature between the Taklimakan Desert and Gurbantunggut Desert, i.e. the temperature increased and decreased very fast, but the transfer depth of them is lower than that of the Naiman Desert. From the temperature profiles of sand layer, the ground temperature reduced steadily below 40 cm of sand layers of Taklimakan Desert and Gurbantunggut Desert, showing no signal of diurnal variation, however, the heat transmission effect was obvious below 50 cm of the Naiman Desert[26].

3.3 The characteristics of the specific humidity profiles

Located at the Eurasia hinterland, the Taklimakan Desert is far from the ocean, exhibiting extreme arid inland climate. Figure 4 shows the average specific humidity profiles of surface layer atmosphere of August, 2006. It was indicated that the specific humidity decreased with the height below 32 m of the surface layer, but the variation range was small. The average specific humidity was not large at 0.5 m at 20:00 pm; however, specific humidity below 10 m of the surface layer soared up with time, reaching its maximum at 08:00 am, which may be because the daytime temperature in summer was high, the turbulence was strong, and water vapor was less comparatively. A small amount of water evaporated into upper atmosphere after sunrise in the morning, which went to the surface layer subjected to the small influence of the down draft before sunrise. This led to the increase of the water vapor early in the morning. Another possibility was that there was little water vapor in the sand surface

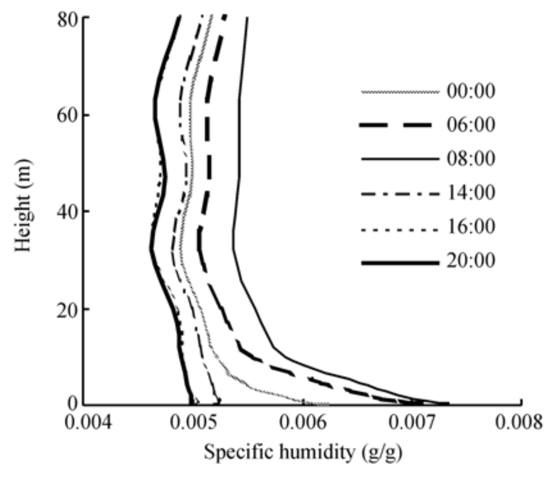

Figure 4 The average specific humidity profiles of every gradient of August, 2006.

and layer, the moisture was reduced by the evaporation, which stopped at night. The deep moisture moved upward slowly, by 08:00 am, the moisture in the sand layer peaked. Hence with more evaporation, the content of moisture increased, and was added by the original moisture, then peaked in the morning. This explanation needs further verification. The humidity near the ground reduced very fast because of the quick increase of the ground temperature after sunrise at 10:00 am, the average specific humidity gradient declined.

3.4 The characteristics of the surface radiation balance

Figure 5 shows the diurnal variation characteristics of every natural solar radiation of the Taklimakan Desert during August 13—31, 2006 (All the time referred below is local time). It is necessary to note that for all the 19 days, there were 10 days with floating dust, sand blowing and sandstorm of various degrees, 2 days with shower and 7 days with no weather phenomena. It can be seen from Figure 5 that the balance of the surface radiation was mainly positive, slight minus balance occurred at night, demonstrating standard diurnal cycle morphology; the total radiation peaked at 709 $W \cdot m^{-2}$; the peak value of the surface reflective radiation could be above 150 $W \cdot m^{-2}$; the atmospheric downward long wave radiation leveled at 350—400 $W \cdot m^{-2}$ basically, which showed a slight increase during the daytime; the upward surface long-wave radiation was above 400 $W \cdot m^{-2}$, the peak value of the daytime could exceed 600 $W \cdot m^{-2}$, and the biggest variation was above 200 $W \cdot m^{-2}$. Thus, the upward surface long-wave radiation was the main part of the long-wave radiation, which was bigger in the daytime, bottomed at 06:00 am and peaked at 13:00 pm. The peak value occurred when the temperature of desert surface was highest. The peak value of the net radiation reached 317 $W \cdot m^{-2}$ at around 12:00 am, the average of which was only 60.7 $W \cdot m^{-2}$, the transform from positive to negative was at 06:00 am, the reverse occurred at 18:00 pm. So, although the total radiation of the Taklimakan Desert was very large, the net radiation was comparatively small due to the large reflective radiation during the day and comparatively large upward surface long-wave radiation.

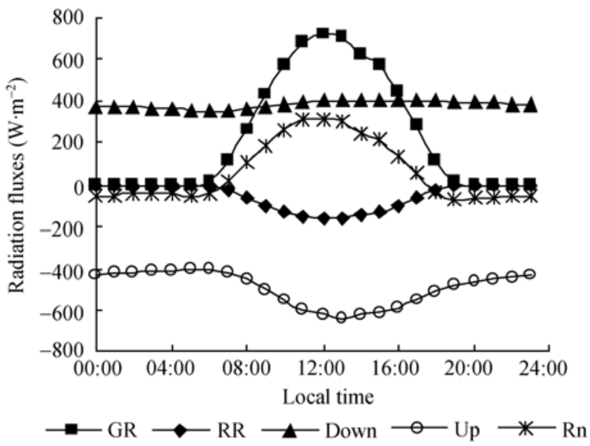

Figure 5 The average diurnal variation curve of radiation balance. GR, Global radiation; RR, reflective radiation; Down, downward long wave radiation; Up, upward long wave radiation; Rn, net radiation.

3.5 The diurnal variation characteristics of the sensible heat flux (*H*) and latent heat flux (*λE*)

(i) The diurnal variation of the sensible heat flux (*H*). Figure 6 shows the average diurnal variation results of the surface sensible heat and the latent heat of the Taklimakan Desert during 13—31 of August, 2006, which were calculated by the combination method. As shown in Figure 6, the diurnal variation of the sensible heat flux of Taklimakan Desert was identical with the common situation, increasing gradually in the morning, peaking around noon (local time) and then starting to decline. Because the ground gained more solar radiation with the increase of the sun elevation angle after sunrise, in addition, the turbulent movement was stronger in the afternoon, the ground temperature peaked and the heat transferring to the surface boundary layer reached the maximum as well. Then, the ground gained less solar radiation gradually because of the decrease of the sun elevation angle, the ground temperature declined, and so did the sensible heat flux. The maximum and the minimum of the sensible heat flux were 152.51 $W \cdot m^{-2}$ and −24.94 $W \cdot m^{-2}$ respectively, and the daily average was 44 $W \cdot m^{-2}$.

(ii) The diurnal variation of the latent heat flux (*λE*). It was illustrated by the diurnal variation curve of the latent heat flux (Figure 6) that the variation of the latent heat flux of the Taklimakan Desert was comparatively complicated, but there were a maximum and a minimum, which occurred at 08:00 am and 20:00 am (local time). It was dominated by the surface latent heat transfer to the atmosphere, which was related to the higher ground temperature than the surface boundary layer. However the peaked value of the latent heat flux was merely 58.73 $W \cdot m^{-2}$, and the daily average was 11.31 $W \cdot m^{-2}$. This was closely related to the aridity of the surface of the Taklimakan Desert and the lack of moisture in the air.

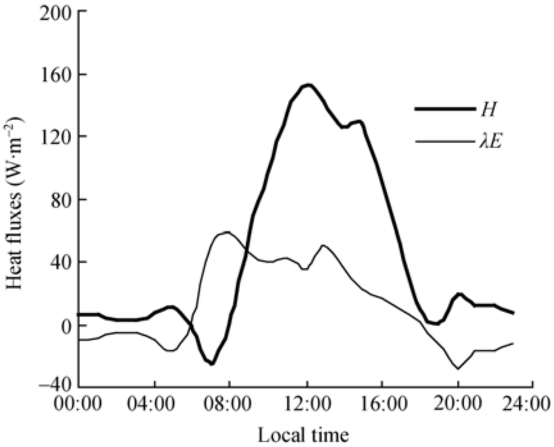

Figure 6 The average diurnal variation curve of sensible heat and latent heat.

By making a comparison between the daily average sensible heat flux and latent heat flux on three different underlying surfaces (Table 1), it can be seen that the daily average sensible heat flux and latent heat flux of the Taklimakan Desert were lower than those of the experimental region of Heihe Gobi and deserts, but the sensible heat flux was higher and the latent heat flux was lower than those of Heihe oasis experimental region.

3.6 The characteristics of the surface heat balance

Figure 6 indicates that sensible heat flux dominates over latent heat flux in the daily average changes, the net radiation flux diffused mainly in the form of turbulent sensible heat, the sensible heat flux, latent heat flux and soil heat flux accounted for 72.5%, 18.6% and 8.9% of the net radiation flux respectively, which demonstrated that the main part of the solar radiation energy was transferred to the surface boundary layer in the form of sensible heat in the Taklimakan Desert, a part of the rest was transferred to the underground in the form of geothermal flow, only 18.6% of the released as latent heat. It is interesting to note that the surface latent heat peaked at around 07:00 am (local time) at 58.73 $W \cdot m^{-2}$, the maximum of the day, meanwhile, the variation direction of the sensible heat was the opposite, manifested as wave vale trough at –24.94 $W \cdot m^{-2}$. During the whole process of diurnal variation, the surface heat and latent heat fluctuated with the change of sun elevation angle. The special form of heat diurnal variation of the underlying surfaces was demonstrated in the form of the small peak of the latent heat and big peak and small wave trough of sensible heat.

3.7 The surface heating field

The heating effect of the underlying surfaces of the Taklimakan Desert has great influence on the climate of northwest regions in China. The heating effect of the desert underlying surfaces was determined by the turbulent process and the radiation process[27]. R_n–G_0 is referred to as the surface heating intensity (R_n is net radiation flux, G_0 is soil heat flux), when R_n–G_0>0, heat was transferred from ground to air, the ground was the heat source for air; whereas, when R_n–G_0<0, the ground was the cold source for air. Figure 7 shows the change law of the diurnal variation of surface heating field of the Taklimakan Desert. From Figure 7, the ground was a strong heat source during the day, the heating effect of the ground to the air was obvious. After the sunrise in the morning the surface heating field became stronger gradually especially at around 13:00 pm (local time), the heat intensity peaked, above 192 $W \cdot m^{-2}$. The surface heating field declined gradually, after 19:00 pm (local time), the ground turned a slightly cold source.

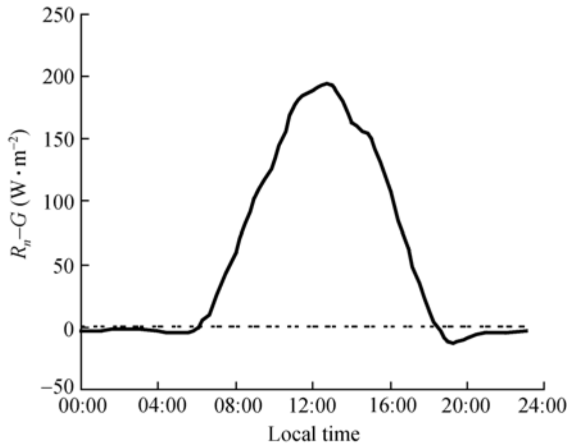

Figure 7 The average diurnal variation curve of the surface heating field intensity.

Table 1 The comparison between the sensible heat flux and latent heat flux on three different underlying surfaces

Place name		Time	Daily average H ($W \cdot m^{-2}$)	Daily average λE ($W \cdot m^{-2}$)
Heihe	Gobi	Aug. 17, 1991	66.2	30.5
experimental	Desert	Aug. 17, 1991	62.2	30.2
region	Oasis	Jul. 8, 1991	22.4	145
Taklimakan Desert		Aug. 13－31, 2006	44	11.31

4 Conclusions

According to the calculation and analysis of the gradient data of wind, temperature and humidity, ground surface temperature data and radiation and heat data obtained from 80 m iron tower at the Atmospheric Environmental Observation Station of Taklimakan Desert during July-August of 2006 and 2007, the following conclusions can be drawn:

(1) The temperature inversion occurred near the ground surface due to the fast cooling of the under lying surface of the desert at night in summer. The temperature increased with the height in a certain height range; the temperature gradient varied greatly below 20 m, the reverse was true above 20 m. The average specific humidity of the surface boundary layer decreased with the height increasing before reaching 32 m, when the average specific humidity increased with the height increasing, but within a comparatively small range.

(2) The temperature diurnal variation of the sand layer was obvious, the vertical temperature distribution decreased downward in daytime and the reverse was true at night, the temperature diurnal variation of the sand layer occurred most evidently at 0 cm and 5 cm, there was no change signal below 40 cm. The observation and analysis showed that the zero interface of heat transfer occurred at 20 cm when the largest surface sensible heat flux peaked.

(3) The radiation balance of the surface layer of the Taklimakan Desert was mainly positive; other natural solar radiations (the global radiation, reflective radiation, the atmospheric counter radiation and the net radiation) exhibited daily variation characteristics evidently and showed normal diurnal cycle form, except the downward atmospheric long-wave radiation. The maximum total radiation was above 700 $W \cdot m^{-2}$, the net radiation was 317 $W \cdot m^{-2}$, and the daily average was 60.7 $W \cdot m^{-2}$.

(4) The main energy exchanging form was land-air sensible heat exchange in the Taklimakan Desert, the latent heat was comparatively small. The sensible heat and latent heat exhibited the positive and negative exchange process of the drafting desert heat with the change of the sun elevation angle. The sensible heat balance was mainly positive and became negative at wee hours, demonstrating the special form of heat diurnal variation of the underlying surfaces, which peaked at around 12:00 am (local time) of the day; whereas the latent heat balance was positive during the day and negative at night, of which the maximum and minimum values occurred at 07:00 am and 20:00 pm respectively.

(5) The heating effect of the underlying surface on the air was obvious in the Taklimakan Desert; the ground was a strong heat source during the day and a slightly cold source at night.

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