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Relationship of atmospheric boundary layer depth with thermodynamic processes at the land surface in arid regions of China

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The atmospheric boundary layer (ABL) is an important physical characteristic of the Earth's atmosphere. Compared with the typical ABL, the ABL in arid regions has distinct features and is formed by particular mechanisms. In this paper, the depth of the diurnal and nocturnal ABLs and their related thermodynamic features of land surface processes, including net radiation, the ground-air temperature difference and sensible heat flux, under typical summer and winter conditons are discussed on the basis of comprehensive observations of the ABL and thermodynamic processes at the land surface carried out in the extreme arid zone of Dunhuang. The relationships of the ABL depth in the development and maintenance stages with these thermodynamic features are also investigated. The results show that the depth of the ABL is closely correlated with the thermodynamic features in both development and maintenance stages and more energy is consumed in the development stage. Further analysis indicates that wind velocity also affects ABL development, especially the development of a stable boundary layer in winter. Taken together, the analysis results indicate that extremely strong thermodynamic processes at the land surface are the main driving factor for the formation of a deep ABL in an arid region.

arid region, deep atmospheric boundary layer, development and maintenance, thermodynamic process at the land surface, main driving factor

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The atmospheric boundary layer (ABL) is one of the most important physical characteristics of the Earth's atmosphere and closely related to the formation and evolution of weather and climate. Therefore, its depth has been one of the important physical parameters in atmospheric numerical simulation and environment evaluation. Earlier studies have generally shown that the depth of the diurnal convective boundary layer (CBL) is of the order of 1000 m, while that of the nocturnal stable boundary layer (SBL) is of the order of 100 m [1]. However, studies on the ABL under special geographical conditions and extreme climatic conditions during the past 10 years have gradually changed the past point of view [2–5]. For example, Takemi's study [6] on ABL characteristics of the arid region of the Hexi Corridor, Northwest China, inferred that the depth of the CBL is more than 4 km from conventional meteorological sounding data of characteristics of the residual layer. In the NWC-ALIEX experiment conducted in 2000, Zhang et al. [7] also observed that the diurnal CBL has a depth greater than 4 km

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on sunny summer days and that the nocturnal SBL can have a depth over 1 km in Dunhuang, an extreme arid region in Northwest China [8]. To further confirm the reliability and universality of such observations, the same research team investigated the characteristics of the ABL in Dunhuang in 2006–2007 [9, 10] using a more advanced L-band radar sounding system and satellite remote sensing of temperature profile technology. Their results confirmed the prevalence of a deep CBL during the sunny summer period and found that the depth of the CBL in winter is less than one-fourth of that in summer. In the similarly arid Sahara Desert, Marsham et al. [11] observed a CBL up to 5.5 km deep and an evident residual layer and concluded that the deep CBL is related to an intense solar radiation background and extremely dry land surface [12–18].

Research on the formation mechanisms of a deep ABL over the arid region in Northwest China is rather preliminary, especially in terms of the role of the land surface. This not only significantly limits our understanding of the interaction between the deep ABL and the climate, but also impedes parametric improvement of the numerical model of deep ABL characteristics. Utilizing the comprehensive data obtained in the project "Experimental observations of the ABL in Dunhuang" [19], this paper attempts to analyze systematically the interaction characteristics of thermodynamic processes in the ABL development and maintenance and further study the physical mechanism of deep ABL formation in arid regions.

1 Observation fields, data and methods

Data used in this paper were obtained from "Experimental observations of ABL in Dunhuang", a comprehensive observation project on the ABL and land surface processes supported by the National Natural Science Foundation [9, 19]. The observation area is the center of the arid region in Northwest China, which is located at 40°10′N and 94°31′E, has an altitude of 1140 m and is a typical extreme arid region in the mid-latitude climate zone with abundant sunshine. The region has annual average rainfall of less than 40 mm, annual average sunshine percentage as high as 75% and annual sunshine time exceeding 1114.2 h. The area has great evaporation potential, with the annual average evaporation being as high as 3400 mm. The annual average ground temperature is 12°C, and the mean temperature difference between winter and summer is more than 40°C. The annual average ground wind speed is about 2.7 m s^{-1}.

Figure 1 shows the experimental observation area and its geographical environment. The observation field is located in Shuangdunji Gobi Desert, 7 km west of the oasis of Dunhuang. Because the field is windward of the oasis, its energy, water and material exchanges are not affected by the oasis climate. Therefore, the field observation data represent the characteristics of land surface processes in the

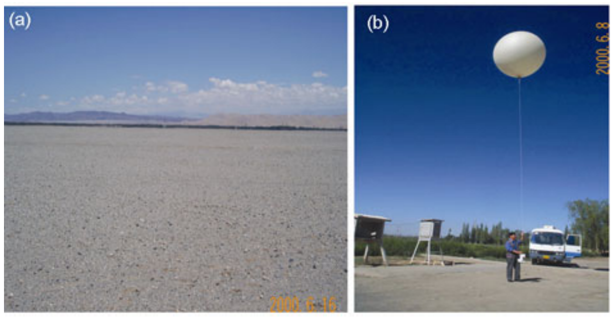

Figure 1 Geographical environment (a) and observation field (b) of the project "Atmospheric Boundary Layer Experiment in Dunhuang".

Gobi Desert. The field was equipped with near-surface layer flux and radiation balance observation apparatuses. The near-surface layer flux was observed with a CSAT3 three-dimensional sonic anemometer (Campbell Scientific, Inc.) set 2.5 m above the ground. Radiation was monitored with a PSP solar radiation measurement instrument (Eppley Laboratory, USA) set 1.5 m above the ground. Meanwhile, boundary layer meteorological factors including temperature, humidity, wind speed, wind direction and air pressure were observed by the Dunhuang city weather station equipped with a GFE(L)1 secondary wind finding radar sounding system and a radiosonde-L-band radar system composed of a GTS1 digital radiosonde sounding instrument in the eastern suburb of Dunhuang. The atmospheric radiosonde-L-band radar system used is a high-altitude weather detection apparatus developed independently in China [20, 21]. Compared with the previously used "59"-type mechanical sounding instrument, the GTS1 digital electronic sounding instrument can more accurately measure temperature, pressure, and humidity in a broader range with better temporal and spatial resolution; therefore, it is suitable for ABL observations in arid regions. Data were collected every 10 m from 8680 m above ground at 7 am, 9 am, 11 am, 3 pm, 5 pm, 7 pm and 9 pm Beijing time every day in summer from June 28 to July 17, 2006 and in winter from January 1 to January 10, 2007.

To compare the spatial distribution differences of the ABL, data were also collected from Jiuquan, Minqin, Yuzhong and Pingliang using the same instrument during the same period. The observation days were sunny except for rainy days on July 5–7, 2006 and cloudy days on January 1–3, 2007. Because of the importance of thermodynamic processes in the ABL development and maintenance and clear characteristics of the ABL potential temperature (PT) profile in the arid area, the PT profile was used to determine the depth of the ABL [22, 23]. In detail, the depths of the diurnal CBL were measured at 11 am, 1 pm, 3 pm and 5 pm. The layer that has an obvious PT jump or dog-leg path bottom of the temperature inversion along with atmospheric temperature inversion greater than 0.3°C/100 m was considered as the boundary of the CBL; the height of the layer that had constant but near-zero PT and specific humidity was defined as the maximum depth of the ABL, as shown in Figure 2(a). The depth of the nocturnal SBL was measured at 7 am, 9 am, 7 pm and 9 pm. The top layer of the inversion PT with strength greater than 0.4°C/100 m was defined as the boundary of the SBL. The height between this layer and the ground was determined to be the height of the SBL [14], as shown in Figure 2(b). The neutral atmosphere above the top of the SBL but beneath another weak layer of inversion PT was considered to be the residual layer [14, 15].

2 Results

2.1 Characteristic comparison of diurnal changes in the ABL depth and land surface thermodynamic factors

The land surface thermodynamic process mainly refers to the transformation of solar radiation energy into thermal energy at the land surface and subsequently the atmosphere and soil. In this process, the net radiation (R_n) formed during energy transformation is the foundation of thermal energy at the land surface. The ground-air temperature difference (ΔT) due to surface radiation heating (or cooling) is the thermodynamic force for the formation of the thermal CBL or inversion layer (IL), and the near-ground turbulent sensible heat flux (H_s) is responsible for the maintenance of the thermal CBL or IL. Therefore, from a physical point of view, the formation and development of the ABL is closely related to R_n, ΔT and H_s at the land surface.

Figure 3 shows the relationships of the diurnal changes of R_n, ΔT and H_s with the ABL depth. To facilitate analysis, the depths of the CBL and SBL are shown as positive and negative values, respectively. As shown, R_n, ΔT and H_s have good correlation with the ABL depth in both summer and winter. Larger diurnal R_n, ΔT and H_s correspond to a deeper CBL. Similarly, larger absolute nocturnal R_n, ΔT and H_s correspond to a deeper SBL. The ABL development is about 2 h behind R_n and 1 h behind ΔT and H_s, perhaps owing to the lag of the energy distribution, conversion and transportation from the land surface to the atmosphere [24]. To simplify the description, the phases of these three variables are synchronized to the change in the ABL depth in the remainder of the paper.

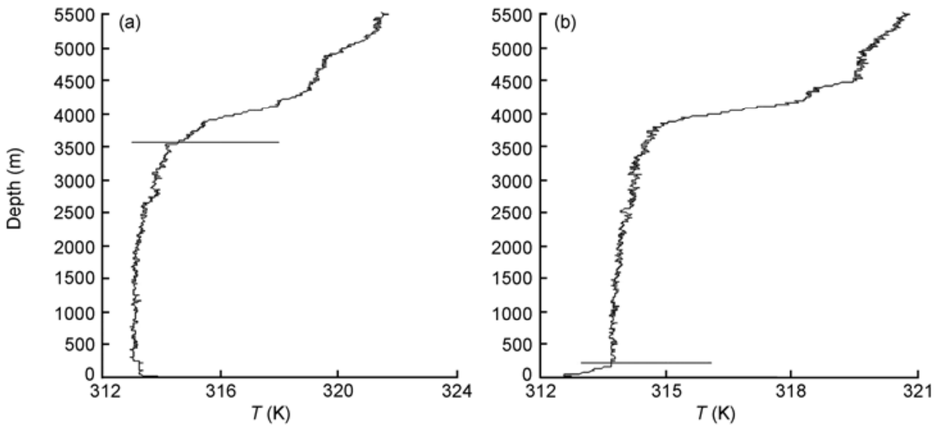

Figure 2 Determination of the convective boundary layer (a) and stable boundary layer (b) using temperature profile technology.

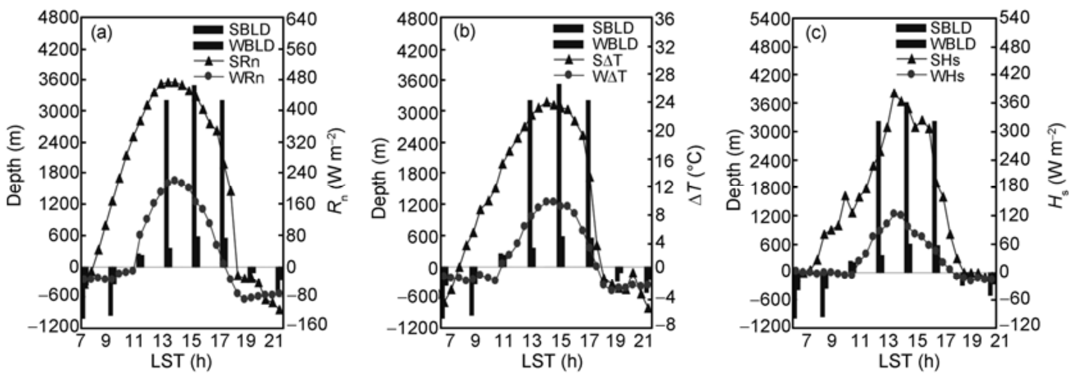

Figure 3 Relationships of the diurnal variation in net radiation (R_n) (a), ground-air temperature differences (ΔT) (b) and sensible heat flux (H_s) (c) with the depth of the atmospheric boundary layer. Positive and negative values represent depths of the convective boundary layer and depths of the stable boundary layer, respectively.

2.2 Relationship of the development and maintenance processes of the ABL with land surface thermodynamic factors

Because thermodynamic processes at the land surface have different roles in the ABL evolution, the ABL before reaching its peak is considered as the development stage of the CBL or SBL, while the ABL after its peak is considered as the maintenance or recession stage of the CBL or SBL.

2.2.1 Relationship of R_n with the development and maintenance of the CBL

Figure 4(a) shows the relationship of R_n with the development (left) and maintenance (right) of the CBL in summer. As shown, in the development stage, the depth of the CBL depends obviously on R_n. When the CBL depth is less than 500 m, the development of the CBL is very slow with R_n increasing; when the depth is greater than 500 m, the development is accelerated; when the depth is beyond 2500 m, the development is slow again. This means that before the thermal convection completely breaks into the nocturnal SBL, the CBL development encounters greater resistance and requires more energy to overcome the constraint from the SBL. Once breaking into the residual layer, the development of the CBL is easier and consumes less energy. When the thermal convection is beyond the residual layer, the development is limited by the weak inversion [15]. Figure 4(a) also shows that the breakthrough of the CBL into the SBL requires R_n to be greater than 300 W m^{-2}. The dependence of the CBL depth on R_n in the maintenance stage is not as strong as that in the development stage; the CBL depth only slightly decreases with R_n decreasing, suggesting that thermal inertia plays a role to some extent. These results indicate that R_n as high as 400 W m^{-2} in summer in the extreme arid region leads to the development of the CBL with depth of 3000 to 4000 m.

Figure 4(b) shows the relationship of R_n with CBL development (left) zand maintenance (right) in winter. In the development stage, the CBL is more sensitive to R_n when its depth is greater than 300 m, indicating that after breaking into the nocturnal SBL, the air thermodynamic environment of the residual layer is more favorable for the CBL development [15]. Although the overall trend is similar, the effect of the residual layer in winter is obviously weaker than that in summer.

Figure 4(c) shows the relationship of R_n in summer with the development (left) and maintenance (right) of the nocturnal SBL. As shown, with the absolute Rn increasing, the cooling effect of the land surface radiation increases, the IL extends upward, and the SBL development continues. Meanwhile, in the maintenance stage, with absolute R_n decreasing, the SBL depth remains relatively constant. When Rn is below −60 W m^{-2}, the SBL depth gradually decreases. These results indicate that Rn as low as 120 W m^{-2} in summer in the extreme arid region is the energy provided for the development of the CBL with a depth of approximately 1000 m.

Figure 4(d) shows the relationship of R_n in winter with the development (left) and maintenance (right) of the nocturnal SBL is similar to that in summer. However, the overall development of the SBL with R_n is slower and the depth of the SBL is less than that in summer for the same R_n. This is probably related to a less dry surface in winter than in summer.

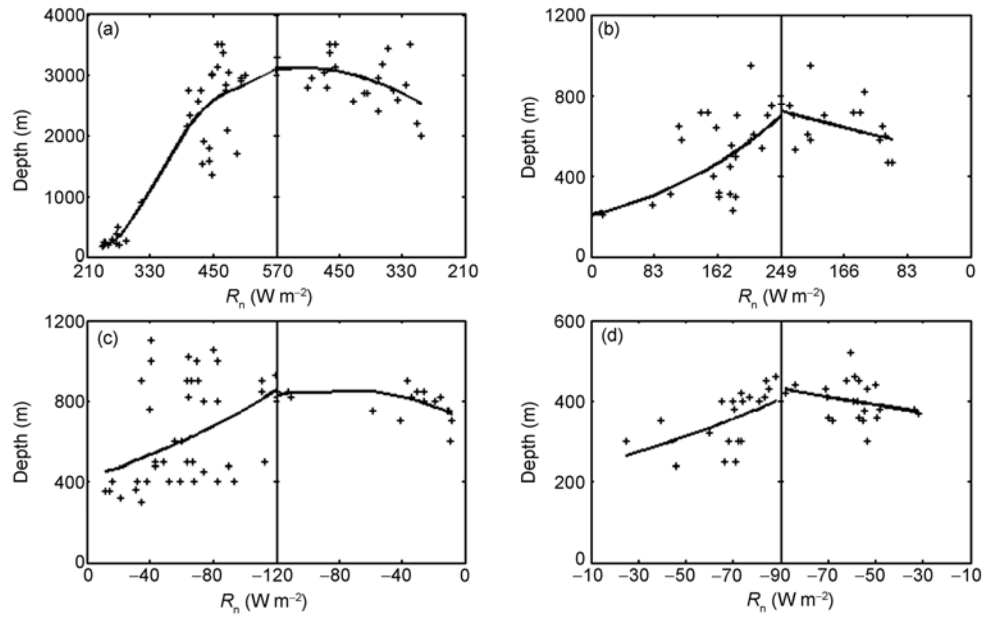

Figure 4 Relationship between net radiance and convective boundary layer and stable boundary layer in development stage and maintenance, declined stage (convective boundary layer in development stage and maintenance, declined stage in summer (a) and in winter (b), stable boundary layer in development stage and maintenance, declined stage in summer (c) and in winter (d)).

2.2.2 Relationship of ΔT with the development and maintenance of the CBL and SBL

A surplus or deficit of R_n can heat up or cool the ground surface. The formation of ΔT and the following thermodynamic force eventually drive the ABL development. Figure 5(a) shows the relationship of ΔT with the development (left) and maintenance (right) of the diurnal CBL in summer, where the air temperature is measured at an altitude of 3 m. As shown, when ΔT exceeds 10°C, the CBL invades the residual layer. When ΔT exceeds 20°C, the depth rapidly increases to more than 3000 m. These observations clearly indicate that ΔT resulting from the greater surplus of ground radiation is the key thermodynamic force for the development of a deep CBL. In the maintenance stage of the CBL, the depth of the CBL is more apparently dependent on ΔT.

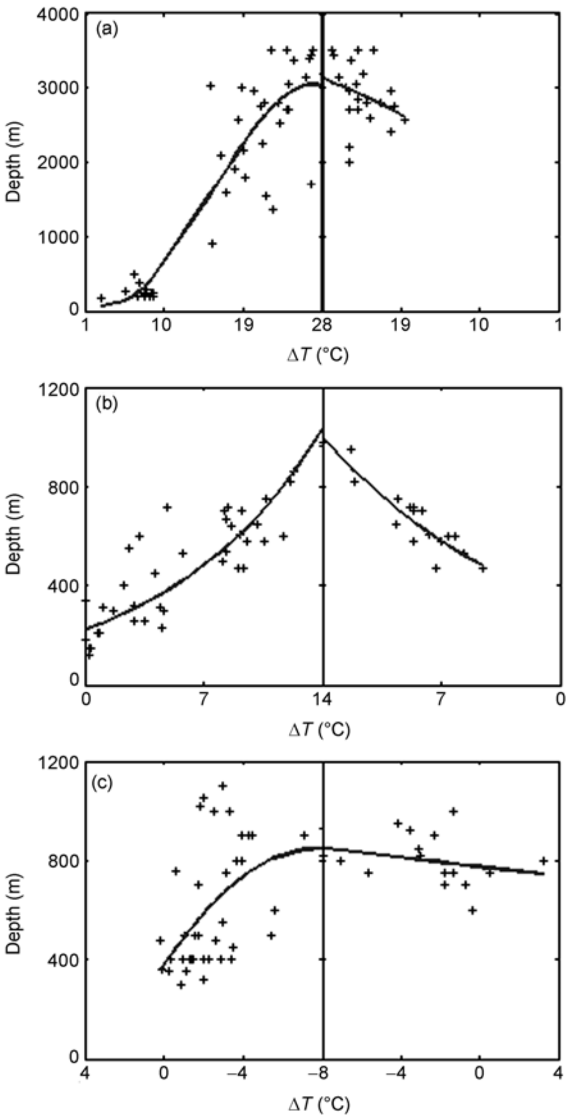

Figure 5 Relationship between ground and air temperature differences and convective boundary layer and stable boundary layer in development stage and maintenance, declined stage (convective boundary layer in development stage and maintenance, declined stage in summer (a) and in winter (b), stable boundary layer in development stage and maintenance, declined stage in summer (c) and in winter (d)).

Figure 5(b) shows the relationship of ΔT with the development (left) and maintenance (right) of the CBL in winter. When ΔT exceeds 5°C or the depth of the CBL is greater than 300 m, the development of the CBL is significantly faster.

Figure 5(c) shows the relationship of ΔT with the development (left) and maintenance (right) of the CBL in summer. Obviously, as the cooling effect of surface radiation increases, increased inversion ΔT causes turbulent diffusion, leading to the upward expansion of the ABL. When the absolute inversion ΔT is less than 5°C, the development of the SBL is relatively slow. It is noteworthy that some of the deepest SBLs appear when ΔT is smaller. In the maintenance stage, the ABL contracted slowly with ΔT decreasing, which is very different from the case for the CBL. Inversion ΔT in winter weakly affects the development and maintenance of the SBL (figure not shown) and is not clearly related to the depth of the SBL. This, to some extent, indicates that in both summer and winter, the turbulence diffusion caused by nocturnal wind shear often has significant effects [8, 12]. The boundary dynamic and land surface thermodynamic effects coexist in the development of the SBL. The dynamic effect plays a dominant role in winter while the thermodynamic effect plays a key role in summer. Therefore, the relationship between the land surface thermodynamic effects and the SBL in winter is more complicated.

2.2.3 Relationship of Hs with the development and maintenance of the CBL and SBL

The development and maintenance of the ABL mainly depend on H_s-induced heat transportation [25–28]. Figure 6(a) shows the relationship of Hs with the development (left) and maintenance (right) of the CBL in summer. As shown, similar to the cases for R_n and ΔT in the development stage, when Hs exceeds 100 W m^{-2}, the CBL breaks the SBL into the residual layer and quickly develops with Hs increasing. When Hs exceeds 250 W m^{-2}, the depth of the CBL is more than 3000 m. In the maintenance stage of the CBL, the contraction of the CBL is more dramatic with H_s decreasing than with R_n decreasing, but less than that with ΔT decreasing. Figure 6(b) shows the relationship of H_s with the development (left) and maintenance (right) of the CBL in winter. As shown, the correlation of H_s in winter with the development and maintenance of the CBL is more obvious than that of R_n and the change in the CBL with H_s is a continuous and uniform process. Figure 6(c) shows the relationship of H_s with the development (left) and maintenance (right) of the SBL in summer. As shown, their relationship is not very clear. An SBL with a depth of 800 m can develop under a weak negative Hs condition. Figure 6(d) shows the relationship of H_s with the development (left) and maintenance (right) of the SBL in winter. As shown, the

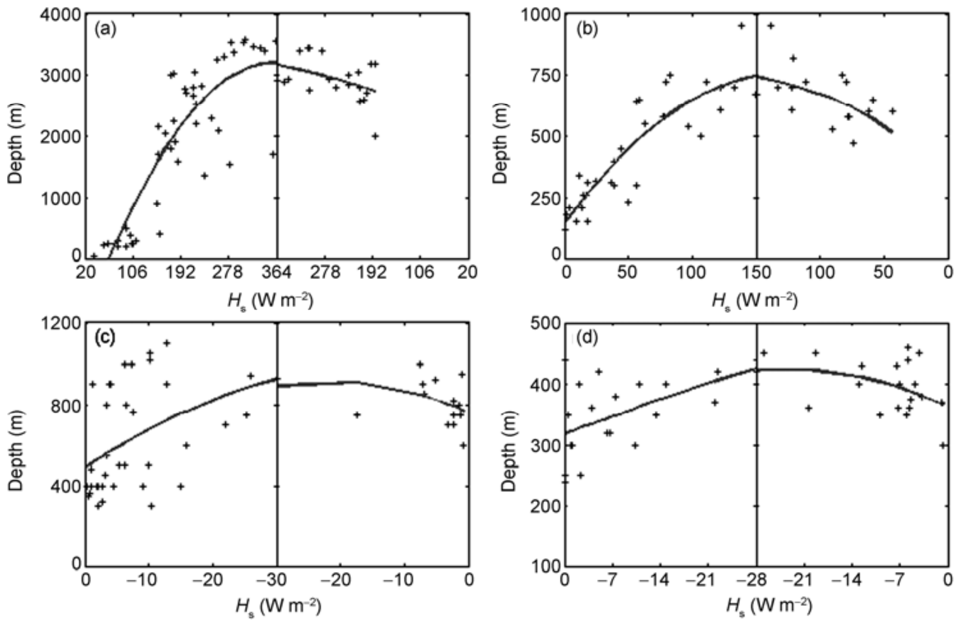

Figure 6 Relationship of the sensible heat flux with the development and maintenance of the convective boundary layer and stable boundary layer. (a) Depth of the convective boundary layer vs. sensible heat flux in summer; (b) depth of the convective boundary layer vs. sensible heat flux in winter; (c) depth of the stable boundary layer vs. sensible heat flux in summer; (d) depth of the stable boundary layer *vs* sensible heat flux in winter.

correlation in winter is similar to that in summer. When absolute H_s is less than 20 W m^{-2}, the depth of the CBL remains virtually unchanged, but the overall depth is much lower than that in summer.

2.2.4 Relationship of the boundary wind speed with the development and maintenance of the ABL

In addition to land surface thermodynamic factors, the dynamic factors of the ABL itself also cause mechanical turbulence and therefore affect the formation and development of the ABL to some extent. Among them, the wind speed is the most important.

Analyses have shown that in summer, the maximum wind speed has no effect on the development and maintenance of the diurnal CBL (figure not shown) but significantly affects the development of the nocturnal SBL (Figure 7(a), left), especially when the wind speed exceeds 10 m s^{-1}; the SBL rapidly expands with the wind speed increasing. Thus, the development of a deeper nocturnal SBL is related to strong mechanical turbulence caused by strong wind. In general, the appearance of strong wind is related to a nocturnal low-level jet, which is consistent with the above analyses on the land surface thermodynamic effects. Therefore, the appearance of a deeper SBL in an arid desert zone is related to the low-level jet found in the region [8]. By contrast, as shown in Figure 7(a), the maintenance of the SBL is not closely related to wind speed; its depth only slightly decreased with wind speed decreasing.

Figure 7(b) shows the relationship of the boundary wind speed with the development and maintenance of the ABL in winter. High wind speed is correlated with a deeper diurnal CBL in the development stage. In the maintenance stage, the CBL contracts more evidently when the wind speed is less than 8 m s^{-1}. This effect may be due to a larger contribution of mechanical turbulence caused by wind shear in winter when the thermodynamic effect is weaker than that in summer.

2.2.5 Effect of the weather on the depth of the ABL

Affected by the elevation angle of solar radiation, R_n, Hs and ΔT have obvious daily variations. Accordingly, as shown above, the change in the ABL depth due to thermal convection also has a clear diurnal pattern. Precipitation and cloudy weather affect the amount of solar radiation reaching the ground, resulting in differences in the surface energy distribution and ABL depth. Figure 8 shows the maximum depths of the CBL and SBL in summer (a) and winter (b) from July 4 to 8, 2006 and January 1 to 3, 2007. Among these days, July 5 had trace precipitation, July 6 and 7 were cloudy, and January 2 was cloudy. As shown, the maximum depth of the diurnal CBL decreased on cloudy and rainy days in both winter and summer. After a cloudy day, the depth increased rapidly. On one hand, less solar radiation reached the ground on cloudy days, which significantly decreases thermal convection, ground humidity and surface latent heat flux, and Hs decreases on rainy days, all leading to a reduced thermal convection zone in an arid region and consequently limited development of the CBL. On the other hand, when low cloud appears on cloudy days, water vapor in the mixing layer increases and the cloud system inhibits the rapid development of the CBL, leading to a thinner CBL. Similarly, on cloudy and rainy days, the maximum depths

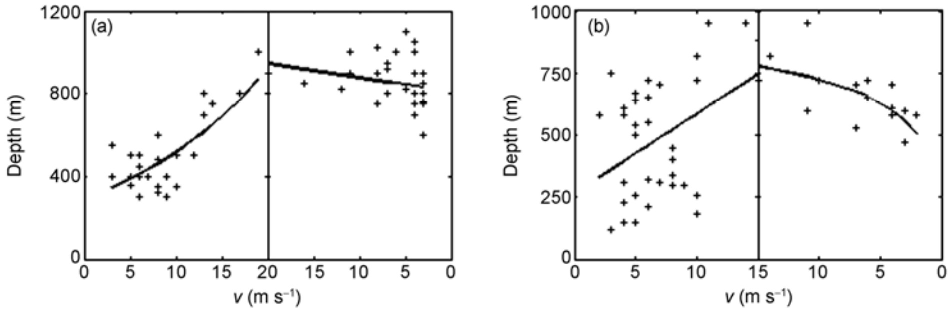

Figure 7 Relationship of the maximum wind velocity with the development and maintenance of the stable boundary layer and convective boundary layer. (a) Depth of the stable boundary layer vs. the maximum wind velocity in summer; (b) depth of the convective boundary layer vs. the maximum wind velocity in winter.

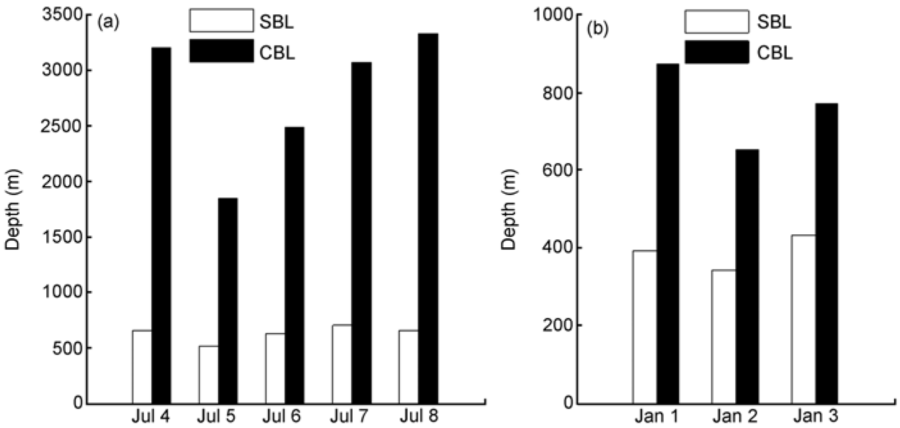

Figure 8 Changes in the maximum depths of ther convective boundary layer (CBL) and stable boundary layer (SBL) in summer (a) and winter (b) during the period of cloudy days.

of the nocturnal SBL are also reduced, but to a smaller extent compared with the changes in maximum depth of the CBL.

2.3 Differential ABL spatial distribution in arid and semi-arid regions in Northwest China

The depths of the ABL were significantly different in Dunhuang, Minqin, Jiuquan, Yuzhong and Pingliang, five extensively observed regions with average annual precipitations of 39.9, 113.6, 87.7, 289.9 and 511.2 mm, respectively. Figure 9 shows the seasonal distribution characteristics of the maximum depths of the CBL and SBL in the arid and semi-arid regions of Northwest China. As shown, the depths of the CBL and SBL basically increase with precipitation decreasing in all seasons. In summer, the average depths of the CBL and SBL in Dunhuang are about 1100 and 500 m greater than those in Pingliang, respectively. By contrast, in winter, their differences are only about 130 and 170 m, respectively. Dunhuang, the most arid region, has the deepest ABL probably because it has longer sunshine hours, more abundant solar radiation and more absorbed surface energy, leading to more dramatic thermodynamic effects on the development of the ABL. In addition, Gamo et al. [4] showed that there is a "hot island" that makes a contribution similar to that of a "worm pool" to El Niño in an arid region. The surface energy processes and the development of the ABL are highly sensitive to soil moisture; i.e. small difference in the spatial distribution of soil moisture may result in a dramatic difference in surface energy and characteristics of the ABL.

In summary, compared with the four other regions, Dunhuang, which has the least precipitation among the arid areas, has an energy basis and dynamic conditions that are more suited to inducing strong turbulence and convection. Therefore, it has stronger diurnal surface radiation heating and nocturnal surface radiation cooling capacities. These factors are favorable for the formation of an extremely deep ABL.

Figure 9 also shows that the depths of the ABL in the five regions are greatest in summer, followed by spring, full and winter. Thermodynamic factors are most important for ABL development. Among them, solar radiation is the source of all energy. Because solar radiation is most intensive and abundant in summer, its thermodynamic effects are most significant in that season. When solar radiation is strong, its induced turbulence is strong, leading to a deeper ABL. However, with the seasonally decreasing elevation

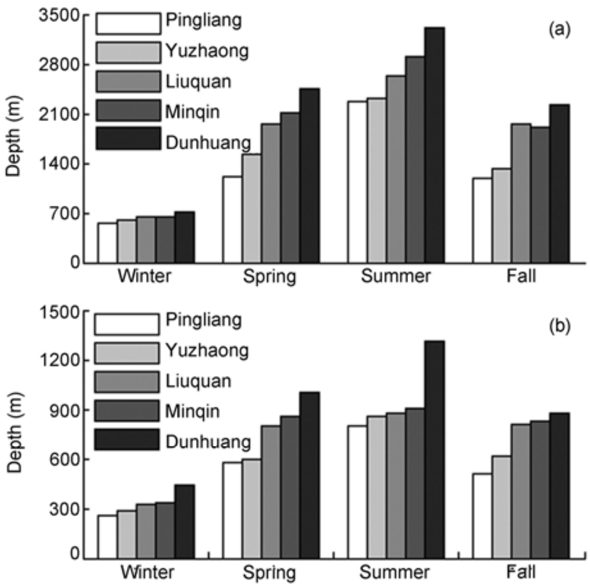

Figure 9 The distributions of seasonal changes of the convective boundary layer (a) and stable boundary layer (b) in Northwest China.

angle of solar radiation, the surface-absorbed solar energy decreases. When solar radiation is weak, the development of turbulence is restricted, resulting in a thinner ABL. In winter, the amount of surface-absorbed solar energy reaches a minimum; therefore, the temperature is low, which greatly reduces the effects of thermodynamic factors on the ABL development. In addition, the low average wind speed and weak turbulent and convectional movements in winter also limit air diffusion and further hinder the development of the ABL. Spring has a long period of sunshine, high average surface temperature, relatively low humidity and greater average wind speed than fall, all of which create a favorable environment for a fully developed ABL. Frequent cold air activities and unstable temperatures along with extremely low temperature events and their associated persistent rainfall and increased humidity in fall are not conducive to the formation of a deep ABL.

3 Conclusions and discussion

(1) In arid areas, because of a lack of cloud-cover in the sky and the dry surface, strong solar radiation along with its significantly responsive thermodynamic process at the land surface becomes the prominent factor in ABL formation and development. Therefore, in both summer and winter, the variations in R_n, ΔT and diurnal H_s correspond well to the depth of the ABL. However, because of the lag response of the ABL to these land surface thermal effectors, their diurnal variation phase is generally 1–2 h ahead of that of the ABL.

(2) In the development stage of the CBL, the CBL depth increases with R_n, ΔT and H_s increasing. By contrast, in the maintenance/decline stage, the CBL depth decreases rather slowly with R_n, ΔT and H_s decreasing; therefore, the CBL is mostly in a maintenance stage. Although the SBL also correspondingly changes with thermodynamic factors, it is much less sensitive than the CBL in the development stage.

(3) In general, when the diurnal CBL breaks the restriction of the SBL and subsequently accesses the residual layer, it develops more quickly and smoothly. The appearance of a deeper CBL in an arid zone undoubtedly is related to very strong thermodynamic factors including S_n, ΔT and H_s. Development and maintenance of the nocturnal SBL is somewhat relevant to the land surface thermodynamic and boundary layer dynamic effects although, in general, the greater the absolute inversion S_n, ΔT and H_s, the deeper the SBL. However, some of the deepest SBLs are observed under the condition of relatively small ΔT, suggesting that the development mechanisms of the SBL are more complicated, which may relate to the turbulent diffusion caused by wind. A low-level jet in the ABL with a speed exceeding 10 m s^{-1} may be important for the formation of a deeper SBL.

(4) In China's arid and semi-arid areas, the depth of the ABL decreases with the climate zone transitioning from an arid region to a semi-arid area. However, the spatial distribution of observation data is not broad and representative enough [29, 30], and some of the associations between the ABL and land surface thermodynamic factors have not been fully demonstrated. Meanwhile, because land surface thermodynamic factors are often coupled with the ABL, further in-depth analysis of the ABL involving simulation experiments using a numerical model is needed to more accurately describe the ABL process.

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