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Turbulent Mechanisms for the Deep Convective Boundary Layer in the Taklimakan Desert

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Abstract The deep convective boundary layer (CBL) in the Taklimakan Desert plays an important role in the climate system in East Asia. Based on the observation experiment and large-eddy simulation, turbulent mechanisms for its formation were revealed in this study. This explained why the daily maximum CBL depth was independent of surface heating. In the late-morning, there was a weak temperature inversion and a near-neutral residual layer (RL) above the CBL. With the development of the CBL, stronger convection could penetrate the RL and even overshoot the top of the RL. The distinctive boundary-layer process entrained free-tropospheric air to warm the RL and then promoted the entrainment of the warmed air in the RL into the CBL. This extra energy supply effectively contributed to the growth of the CBL. With further positive feedback between the CBL and RL depths, a deeper CBL would form in consecutive fair-weather conditions.

Plain Language Summary The atmospheric boundary layer controls the exchange of momentum, heat, and mass between the land surface and the free atmosphere. Contrary to the typical 1,000–2,000 m over land, the convective boundary layer (CBL) in the Taklimakan Desert can reach 5,000 m. By coupling with the Tibetan Plateau, the deep CBL becomes a key component of the climate system in East Asia. Traditionally, it is considered that intense surface heating is the primary reason for its formation, but our correlation analysis shows that surface heating can only maintain a CBL of ~1,800 m. To understand the potential physical processes, we further modeled the development of the deep CBL and found that the presence of weak temperature inversion and near-neutral residual layer (RL) above the CBL are crucial. The distinctive vertical structure leads to a unique boundary-layer process, which entrains warm air from the higher level into the RL and further promotes the warmed air in the RL to be entrained into the CBL. The special energy supply is key to the formation of deep CBL. The results are helpful to understand the land-atmosphere interactions under climate change and improve the numerical weather prediction in northern China and even East Asia.

1. Introduction

Taklimakan Desert (TD), the second-largest shifting sand desert in the world, is located in the central Tarim Basin, north of the Tibetan Plateau, and is surrounded by high mountains in the shape of the letter C (Figure S1 in Supporting Information S1). It is characterized by an extremely arid landscape and is the main source of mineral dust. Through the dynamic coupling with the Tibetan Plateau, the TD has significant implications for the downwind areas, which makes it a key climate region in East Asia (Huang et al., 2014; Liu & Li et al., 2020; Meng et al., 2019; Yang et al., 2020). Moreover, the TD is highly sensitive to climate change. Recently, extreme precipitation events have occurred frequently (Wang et al., 2020; Zhang et al., 2012; Zhou et al., 2019). With the construction of the environment and climate observation network (Yang et al., 2021), it has been found that the land-surface processes and the vertical structures of the atmospheric boundary layer are unique (Liu & Meng et al., 2020; Wang & Lu et al., 2016; Wei et al., 2019). Contrary to the typical 1,000–2,000 m over land, the convective boundary layer (CBL) can reach 5,000 m in summer (Wang & Wei et al., 2016). Combined with the dynamic forcing of surrounding mountains and plateaus, the deep CBL has wide effects on the regional
circulation (Wang et al., 2019), the transport of dust aerosols (Huang et al., 2014; Takemi et al., 2006), aggravating drought (Liu & Li et al., 2020), and ecologic environmental evolution (Xu & Lin, 2021).

Although intense surface heating is the primary reason, the development of the deep CBL is directly affected by various factors and the key factor is distinct for each desert. For example, in the Gobi Desert, it is strong thermodynamic land-surface processes that drive the formation of deep CBL of 3,000–4,000 m (Ma et al., 2011; Zhang et al., 2011), while in the Badain Jaran Desert, the near-neutral residual layer (RL) connected with large-scale temperature advection is crucial for the formation of deep CBL more than 3,000 m (Han et al., 2015; Zhao et al., 2018). In addition, the deep CBL with a depth of 6,000 m in the Sahara Desert is closely associated with the heterogeneous surface albedo (Huang et al., 2010; Marsham et al., 2008; Papangelis et al., 2021). However, existing studies on the deep CBL in the TD mainly focus on the description of the phenomenon and its vertical structure, while the physical processes for its formation remain unclear.

Understanding the mechanisms of deep CBL formation is of great significance for accurately characterizing and quantifying complex land-atmosphere interactions (Couvreux et al., 2014; Xu et al., 2018). Therefore, this study aims to reveal the turbulent mechanisms for deep CBLs in the hinterland of the TD: First, to examine the characteristics of CBL depth in summer; then, to analyze the energy supply for the CBL; and finally, to describe the key physical processes for deep CBL formation.

2. Data and Methods

2.1. Observations

An intensive atmospheric boundary layer experiment was conducted from 1 to 31 July 2016 at the Tazhong meteorological station (39° 00’ N, 83° 40’ E), situated in the hinterland of the TD. The station is surrounded by shifting sand and dunes with a horizontal scale of 20–100 m (Yang et al., 2021). This small-scale heterogeneity has a negligible effect on the spatial variability of CBL (Mahrt, 2000; Margairaz et al., 2020), so the station is well representative. The observation data were collected from the Global Positioning System (GPS) radiosonde system and the eddy covariance system. The GPS radiosonde system was developed by the Beijing Institute of Radio Measurement. Radiosondes were launched 4–6 times per day to obtain the vertical distributions for temperature, humidity, pressure, wind speed, and wind direction (see Table S1 in Supporting Information S1 for launch time and instrument performances). The eddy covariance system (IRGASON, Campbell Scientific, Inc., USA) was mounted on a mast, at a height of 3 m above a relatively flat surface, to measure the wind components, air temperature, and H2O/CO2 mass concentrations at a frequency of 20 Hz.

The raw data from the eddy covariance system were processed over 30 min intervals using EddyPro v7.0.6 (LI-COR Inc., USA) software. The procedure mainly involved error flagging, despiking, double coordinate rotations, Reynolds decomposition, and detrending (block-averaging method). Then turbulent statistics were calculated using the eddy covariance method. Based on the vertical profile of potential temperature observed by radiosonde, the top of the CBL, the top and base of the RL, the vertical range of temperature inversion above the CBL, and the stratification in the RL were determined using the potential-temperature gradient approach (Li et al., 2021, and see Text S1 and Figure S2 in Supporting Information S1 for more details).

2.2. Thermodynamic Growth Model

Neglecting latent heating, radiation, and advection (see Text S2 in Supporting Information S1), the heat conservation equation can be written as (Stull, 1988):

$$\frac{\partial \bar{\theta}}{\partial t} = -\frac{\partial \bar{\omega}' \bar{\theta}'}{\partial z}$$

(1)

where $\bar{\theta}$ and $\bar{\omega}' \bar{\theta}'$ are the mean potential temperature and kinetic sensible heat flux for a given height $z$ and time point $t$, respectively. By successively integrating Equation 1 over height and time and considering the
The variation of air density $\bar{\rho}(z)$ and specific heat capacity at constant pressure $C_p(z)$ with height (Picard et al., 2008; Tsilingiris, 2008), the following equation can be derived (see Text S2 in Supporting Information S1 for derivation):

$$\int_0^{z_1} \bar{\rho}(z) C_p(z) \left[ \bar{\theta}_1(z) - \bar{\theta}_0(z) \right] dz = \int_{t_0}^{t_1} H dt - \int_{t_0}^{t_1} E dt$$

(2)

where $z_1$ is the depth of the CBL, $\bar{\theta}_0(z)$ and $\bar{\theta}_1(z)$ represent the mean potential temperature profiles at time point $t_0$ and $t_1$, respectively; $H$ is the surface sensible heat flux and $E$ is the entrainment heat flux (taking upward flux as positive). The left-hand side of Equation 2 represents the energy required for the development of the CBL by warming (incremental internal energy of the CBL), while the right-hand side is the energy supplied by the surface heating and entrainment heating from $t_0$ to $t_1$, respectively. If first focusing on the surface heating and leaving the entrainment heating for further analysis, the contribution ratio of the surface sensible heat flux to the growth of the CBL by warming, $CR$, is introduced by:

$$CR = \int_{t_0}^{t_1} H dt / \int_0^{z_1} \bar{\rho}(z) C_p(z) \left[ \bar{\theta}_1(z) - \bar{\theta}_0(z) \right] dz$$

(3)

For typical CBL over land, the $CR$ is roughly 80%–90% (Stull, 1988). The obvious deviation from the reference range would imply that there are potential physical processes that impact the development of the CBL. It will be demonstrated in Section 3 that the processes are related to the entrainment.

2.3. Numerical Simulation

The Weather Research and Forecasting model version 4.0 with the Large-Eddy Simulation module (i.e., WRF-LES) was used for idealized simulation. The horizontal domain was 8,000 × 8,000 m² with a 50 m grid spacing and periodic lateral boundary conditions. There were 400 levels in the vertical direction with an 8,000 m model top, which produced a variable vertical resolution of 14–30 m. Rayleigh damping layer was applied above 7,000 m to reduce the reflection of gravity waves from the upper boundary. The model was initialized by the radiosonde (Figure S3 in Supporting Information S1) launched at 05:15 (local time = UTC+6 hr) on 14 July 2016 which was a fair-weather day. The simulation duration was 8 hr, during which sinusoidal surface sensible heat flux was prescribed by fitting the diurnal cycle of eddy covariance measurements. The radiation, microphysics, and cumulus parameterizations were turned off, as the objective of the simulation was to capture the unique boundary-layer processes in the hinterland of the TD.

Based on the simulation results, the joint probability density distribution of the normalized vertical velocity $\hat{w}$ and potential temperature $\hat{\theta}$ was calculated (see Text S3 in Supporting Information S1). If the anomalies of the two variables are caused by independent random processes, the joint probability density distribution should be centrosymmetric relative to the origin in the ($\hat{w}$, $\hat{\theta}$) plane. However, in the low atmosphere, the ideal distribution is distorted by real physical processes (Mahrt & Paumier, 1984). Therefore, various turbulent motions, such as thermals and entrainment, can be identified according to the asymmetry and skewness of the joint probability density distribution (Deardorff & Willis, 1985; Mahrt & Paumier, 1984).

3. Results and Discussion

3.1. Overview of CBL Depth and Its Influencing Factors in Summer

Figure 1a presents the daily variation in the CBL depth at 11:15 and 17:15 in the hinterland of the TD in July 2016. Under fair-weather conditions (marked by solid symbols in Figure 1a and defined by the smooth variation of solar radiation), the CBL commonly developed to 3,000 m and even reached 5,140 m at 17:15 on 1 July. Without the impact of precipitation, floating dust, or clouds, the CBL depths at 17:15 were mostly concentrated at 3,000–4,000 m, while it exhibited large variation at 11:15. Additionally, greater CBL depths at 11:15 tended to occur on fair-weather days, while deeper CBLs at 17:15 also developed under cloudy weather, such as on 11 and 19 July. This implies that there may have been different factors driving the development of the CBL during the two periods.
Figures 1b–1e shows the relationship between the CBL depth and possible influencing factors, including the surface sensible heat flux, the top of the RL around the sunrise, and corresponding stratification in the RL. At 11:15, there was a better correlation between the CBL depth and time-averaged surface sensible heat flux, which depended on the depth at <1,800 m (Figure 1b). Once the depth exceeded the threshold, the correlation disappeared. Moreover, the daily maximum CBL depth, which was observed at 14:15 or 17:15, was also independent of surface sensible heat flux (Figure 1c). When surface sensible heat flux exceeded 180 W m$^{-2}$, the daily maximum CBL depth seemed to decrease with the increased surface sensible heat flux. This is because the points on the lower right-hand side were accompanied by a shallower RL or more stable stratification in the RL. Therefore, a larger surface sensible heat flux could promote the growth of the CBL in the early stage, but it cannot determine the final depth of the CBL. Nevertheless, the daily maximum CBL depth exhibited a significant dependence on the top of the RL and the stratification in the RL around the sunrise (Figures 1d and 1e). Greater RL depths and weaker stratification corresponded to deeper CBLs. To further understand the influence of surface sensible heating and atmospheric thermal conditions, an improved thermodynamic growth model was adopted to analyze the energy supply for the CBLs in different stages.

### 3.2. Energy Supply for the Development of Deep CBL

Eight fair-weather days (shaded areas in Figure 1a), which were defined by the smooth diurnal cycle of downward solar radiation (Figure S4a in Supporting Information S1) and had six radiosondes per day (Table S1 in Supporting Information S1), were selected for detailed analysis. For each day, three intervals, bound by adjacent sounding times (black dashed lines in Figure 2a), represented different stages during the development of the CBL. The CR over each interval is shown in Figure 2b. There were obvious differences between the CRs for the CBL in the TD and the reference range (80%–90%). According to heat conservation, the development of the CBL can also be impacted by advection, radiation, latent heating, and entrainment heating, apart from surface heating. For selected
fair-weather days without clouds and floating dust in the hinterland of the desert, the effects of the first three factors could be neglected (Text S2 in Supporting Information S1), and so the differences would be attributed to abnormal entrainment. Furthermore, the CRs in the first and third intervals were significantly different, despite similar surface sensible heat flux in the two intervals. The smaller CR in the first interval, on average 61.7%, suggested that there should be other processes that enhanced entrainment heating to supply energy for the CBL, while the CR of slightly >100% in the third interval indicated the presence of the physical processes related to entrainment to compete with the warming of the CBL for energy.

According to the potential temperature profiles, there were also significant differences between the vertical structures of the CBL in the first and third intervals. Because the eight selected days had similar results (Figure S5 and Text S4 in Supporting Information S1), only the vertical distributions of the potential temperature on 14 July

Figure 2. (a) Diurnal variation of surface sensible heat flux, the black dashed lines bound three intervals, and (b) boxplot of the contribution ratio of surface sensible heat flux CR over the three intervals on the eight selected days. Potential temperature profiles at the beginning and end of (c) 08:15–11:15, (d) 11:15–14:15, and (e) 14:15–17:15 on 14 July 2016. Red horizontal lines indicate the top of the convective boundary layer at the end of each interval. The CR is marked at the top left corner.
2016 are presented as an example in Figures 2c–2e. In the first interval, a shallow CBL formed at the bottom of the nocturnal stable boundary layer at 08:15 and gradually grew with a rapid increase in potential temperature. By the end of the first interval, the CBL had eroded the stable boundary layer. Above the CBL, there was a weak inversion (∼1.5 K) and an un-eroded near-neutral RL located between 3,000 and 3,500 m at 11:15. In the third interval, however, the CBL had broken through the RL and was capped by a strong inversion. The temperature inversion was strengthened with the development of the deep CBL. The feature of the CBL in the second interval was a transition between the first and third intervals, and so was the CR (Figure 2b). There were other interesting differences drawing attention: Unexpected warming occurred above the top of the CBL during the first interval, as depicted by the red shaded area in Figure 2c, while there was a typical cooling below the top of the CBL (blue shaded area in Figure 2e) during the third interval.

Based on the above differences, the following process chain was expected: There were potential physical processes that impacted the effects of entrainment by warming/cooling the local air above/below the top of the CBL, leading to the change in the energy sources and sinks for the development of deep CBL in the TD. It was understandable how the process chain worked in the third interval. For the deep CBL capped by a strong inversion, surface heating was not enough to warm it effectively, so the development of the CBL was supported by penetrative convection. The penetrative convection carried cold CBL air into the entrainment layer and the warm air above was entrained into the CBL, leading to the cooling below the top of the subsequently observed CBL (see the blue area in Figure 2e). The process also caused the increase in the potential energy of the CBL, which competed for the energy from surface heating with the internal energy of the CBL. Therefore, the CR was greater than the reference range. However, the chain in the first interval was poorly understood. To gain an insight into the potential physical process, a WRF-LES experiment was performed.

### 3.3. Physical Processes for the Formation of Deep CBL

The representation of the WRF-LES experiment can be verified by comparing the development of the CBL with the radiosonde observations on 14 July 2021 (Figure S6 in Supporting Information S1). Initially, the simulated CBL depth was identical to that observed, despite with a larger potential temperature (∼1.5 K) in the CBL at 08:15. Then, the temperature difference gradually decreased as the CBL developed. After the top of the CBL reached the bottom of the RL, the simulated CBL grew more rapidly. Accordingly, the cooling below the top of the CBL occurred earlier (at 12:15) in the simulation, while the warming above the CBL continued at 14:15 in the observation. Overall, these differences are considered to have no significant effect on the CBL processes because the general structure of the CBL and its development were characterized by the simulation.

Specific motions can be explicitly reflected by the corresponding quadrant, toward which the tail of the joint probability density distribution is skewed (Deardorff & Willis, 1985; Mahrt & Paumier, 1984). As shown in Figure 3a, quadrant I represents warm updrafts that are recognized as thermals in the CBL, excluding the small-scale turbulence distributed around the origin. Typically, with surface heating, thermals develop upward.
from the bottom of the CBL and turn into cold updrafts around the top of the CBL (i.e., penetrative convection in quadrant IV) relative to the increased ambient temperature. With the negative buoyancy, the updrafts are eventually forced to sink down into the CBL, corresponding to the return flow in quadrant III. Meanwhile, the warm air above is entrained into the CBL, which is the entrainment in quadrant II. This series of motions is encapsulated by the boundary-layer process numbered 1 in Figure 3b. In the deep CBL, however, there are distinctive fates for thermals.

Figure 4 shows the joint probability density distribution at different times and heights. Although vigorous thermals were formed at the bottom of the CBL, as depicted in Figure 4a, the subsequent boundary-layer processes were different between 10:15, 11:15, and 12:15. At 10:15, due to the weak inversion above the top of the CBL, thermals developed to 0.95zi, although some had transitioned into penetrative convection (Figure 4c). Stronger updrafts passed through the weak inversion above the CBL, traveled for a distance in the near-neutral RL, and finally returned as the upward kinetic energy was exhausted, causing large negatively skewed \( \hat{\Theta} \) (Figure 4d). This corresponds to Process 2 in Figure 3b. The process greatly weakened the entrainment around the top of the CBL (Figure S7a in Supporting Information S1), which was also suggested by \( \hat{\Theta} \) with symmetrical distribution range (Figure 4c). In this condition, the energy required for the CBL development was mostly provided by surface sensible heat flux, so the CBL depth was better correlated with surface sensible heat flux in the early stage (Figure 1b).

With the growth of the CBL, the distance between the tops of CBL and RL decreased. Strongly penetrative convection could overshoot the top of the RL (approximate 1.1zi) and return downward at 11:15. With the large temperature difference between the CBL and the free atmosphere, this process was depicted by the cold updrafts and downdrafts being separated from the core in Figure 4h. Meanwhile, the warm air in the free atmosphere was entrained into the RL (Figure 4g), which warmed the RL and caused an increase in the potential temperature.
above the top of the CBL (red shaded area in Figure 2c). The warming strengthened the inversion above the CBL and then promoted the entrainment of the warmed air in the RL into the CBL, indicated by the large positive skewed $\theta$ at 0.95$z$, and more developed downdrafts at 0.8$z$, in quadrant II (Figures 4e and 4f, respectively). This series of motions was described by Process 3 in Figure 3b. Accordingly, this process led to two entrainment layers: One was conventional around the top of the CBL, and the other was around the top of the RL (Figure S7b in Supporting Information S1), which was also found in the Sahara Desert (Garcia-Carreras et al., 2015). With the extra energy supplied by this unique process through entrainment heating, the CBL further developed at approximately 11:15 (Figure S6b in Supporting Information S1), and the correlation between the daily maximum CBL depth and surface sensible heat flux disappeared (Figure 1c). Because the process was affected by the top of the RL and the stratification in the RL, the daily maximum CBL depth was significantly correlated with the two factors (Figures 1d and 1e). At 12:15, the CBL was capped by a strong inversion. Without the near-neutral RL, the boundary-layer process (Figures 4i–4l) had returned to the classical condition (Figure 18 in Deardorff & Willis, 1985), which caused the cooling of air below the top of the subsequently observed CBL (Figure 2e). The CBL grew with a significant increase in potential energy rather than internal energy, leading to greater CR (Section 3.2).

For the formation of the near-neutral RL, there are two possible mechanisms: The first is turbulent vertical mixing, that is, the product of the former CBL, and the other is heat transfer, such as advection heating in the lower layer. Based on existing studies, the surface heating was more intense in summer in the TD (Han et al., 2015; Zhao et al., 2018), while the advection/radiation heating was weaker in the hinterland of the TD and on fair-weather days. Therefore, the near-neutral RL was considered as the residual of the daytime CBL. The deep CBL would lead to a deep and near-neutral RL at night, and on the next day, the RL could then further enhance the development of the CBL. This positive feedback between the depths of CBL and RL makes a deeper CBL possible in consecutive fair-weather conditions.

### 4. Conclusions

Based on the intensive atmospheric boundary layer experiment in July 2016 and the WRF-LES model, the formation of the deep CBL and related boundary-layer processes in the hinterland of the TD were illustrated in this study. Overall, the deep CBL of more than 3,000 m occurred frequently and even reached over 5,000 m in the TD. In the early stage of CBL development, there was a better correlation between the CBL depth and surface sensible heat flux because surface heating could warm a shallow CBL effectively. As the CBL developed further, the correlation disappeared and the contribution ratio of surface heating to CBL growth was only about 60%. It is because there was a special boundary-layer process providing extra energy, in response to the weak temperature inversion and near-neutral RL above the CBL. Strongly penetrative convection could overshoot the top of the RL and entrain free-tropospheric air into the RL to promote the entrainment around the top of the CBL. In this condition, the near-neutral RL acted as a buffer zone between the CBL and the free atmosphere. It absorbed heat from the free atmosphere and transported it to CBL, while avoiding the inhibition of strong capping inversion on the growth of the CBL. It was significant for the formation of deep CBL.

### Data Availability Statement

All data are available at https://doi.org/10.5061/dryad.gf1vhhm7 (Zhang et al., 2022). The Weather Research and Forecasting model version 4.0 is available at https://www2.mmm.ucar.edu/wrf/users/download/get_sources.html#current.

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