Study on Physical Mechanism of Influence on Atmospheric Boundary Layer Depth in the Arid Regions of Northwest China*

Zhang Qiang[1,2](张 强), Wang Sheng[1](王 胜), and Li Yanying[1](李岩瑛)

1 *Key Laboratory of Arid Climatic Change and Reducing Disaster of Gansu Province, Institute of Arid Meteorology, CMA, Lanzhou* 730000

2 *Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou* 730000

(Received April 7, 2005; revised August 8, 2005)

ABSTRACT

Using the sounding data of wind, temperature, and humidity in the boundary layer and micrometeorological data on the earth's surface observed in the same period in Dunhuang arid region of Northwest China, this paper researches characteristics of potential temperature, wind, and humidity profiles, confirms the structure and depth of thermodynamic boundary layer in Dunhuang region, and analyzses the relationship of depth of thermodynamic boundary layer with surface radiation, buoyancy flux as well as wind speed and wind direction shear in the boundary layer. The results show that the maximum depth of diurnal convective boundary layer is basically above 2000 m during the observational period, many times even in excess of 3000 m and sometimes up to 4000 m; the depth of nocturnal stable boundary layer basically maintains within a range of 1000-1500 m. As a whole, the depth of atmospheric boundary layer is obviously bigger than those results observed in other regions before. By analyzing, a preliminary judgement is that the depth of atmospheric thermodynamic boundary layer in Dunhuang region may relate to local especial radiation characteristics, surface properties (soil moisture content and heat capacity) as well as wind velocity shear of boundary layer, and these properties have formed strong buoyancy flux and dynamic forcing in a local region which are fundamental causes for producing a super deep atmospheric boundary layer.

Key words: arid region of Northwest China, depth of boundary layer, buoyancy flux, wind velocity shear, dynamic forcing

1. Introduction

The human activities mainly take place in the atmospheric boundary layer (ABL), and highly rely on the natural environment suitable for human life created by the ABL. Since turbulence transports energy in ABL, surface heating and cooling processes are responded fully and rapidly by the atmosphere, and human are able to live in a relative homogeneous temperature environment. Similarly, turbulent motion transports substances in the ABL, human are able to avoid from disturbing of air pollution created by themselves. The structure, state, and changing process of ABL play an important role in human survival and development. In the atmospheric layer, the depth of ABL is a very important structure feature that decides not only the spatial scale of ABL, but also the capacity of atmospheric environment.

The ABL is a bridge of exchanging substances and energies between earth and atmosphere. Either climatic change or atmospheric circulation is not independent of the contribution of ABL's process, even the forming of sandstorm is also related to the special contribution of ABL. Therefore, the depth of ABL is often focused by meteorologists and environmental scientists.

In atmospheric numerical models, the key of ABL parameterization is the parameterization of atmospheric turbulent diffusion coefficient. The depth of ABL, in general, is one of the most important parameters related to the parameterization of atmospheric turbulent diffusion coefficient (O'Brien, 1970). There are predictive equations about depth of the ABL in most of atmospheric models, however, this kind of equation generally is an iterative one which needs to

*Supported by the National Natural Science Foundation of China under Grant Nos. 40575006, 40233035, the Key Project of the Minisery of Science and Technology of China under Grant No. 2004BA901A16, and the National Key Program for Developing Basic Sciences under Grant No. G1998040904-2.

be given an approximate value of the depth in advance (Tennekes and Driedonks, 1981; Vogelezang and Holtslag, 1996). Furthermore, most of existing predictive equations for depth of ABL are more ideal and far from perfect. They include many uncertain suppositions, lack the actual basis in forecasting ABL in special areas, and many improvements are needed to do. But many improvements are still dependent on observations and cognizance of ABL depth in some representative regions.

Radiation background and surface state are rather special in arid regions (Zhang and Cao, 2003), and it is possible to form the ABL depth different from that of other regions. The global coverage of arid region is rather wide and its ABL depth is obviously different from that of other regions (Wyngaard, 1980), which has strong influence on global changes and atmospheric circulations. However at present there are still inadequate international researches on ABL over arid regions. The structure and depth of ABL in arid regions of Northwest China are still at preliminary stage (Wang et al., 1994; Pan et al., 1992). Because of problems about observational data, field experiments, such as HEIFE etc., only have quite a limited recognition of the structure in the ABL, and even have not determined the integrated daily variation process of depth of ABL.

2. Data

Data analyzed in this paper are surface micrometeorological data and those sounded by small balloons in the ABL of Dunhuang region in arid Northwest China in May-June 2000, which were obtained in Dunhuang, Gansu Province during the intensive observational period from May 25 to June 17 (briefly called "Dunhuang Experiment") (Zhang et al., 2001; Zhang and Hu, 1992) by "the Observational Experiment on the Land-Atmosphere Interaction in Arid Region of Northwest China" that is one of the chief experiments of "Research on the Formation Mechanism and Prediction Theory of Major Climatic Disasters in China" in the national key programs for developing basic sciences.

Dunhuang is located in the middle part of arid region of Northwest China, which is one of the most extreme arid regions in middle and low latitudes. It has sufficient sunshine, but it is dry and a little precipitation, with mean annual precipitation less than 40 mm, and its potential annual evaporative power is as high as 3400 mm, being one of the most frequently occurring places of sandstorm.

Small-balloon sounding observation site of the boundary layer in Dunhuang Meteorological Bureau is located at 40°9′N, 94°41′E with an elevation of 1140 m above sea level and a mean surface pressure of 873 hPa. The site is on bare soil with cropland around dozens of meters away. The small balloon sounded data contain many meteorological elements such as wind speed, wind direction, temperature, relative humidities and barometric pressure. The minimum sounding height required is 5500 m, with one record over every 50 m while below 1000 m and one record over every 150 m while above 1000 m. The instrumental errors of atmospheric pressure, temperature, and relative humidity are 0.1 hPa, 0.4°C, and 3%, respectively; the errors of wind speed and wind direction observed by radar are 1 m s^{-1} and 0.6°, respectively. The valid observational time intervals, from May 29 to June 4 and 8-9, contain nine complete days altogether. Observation per day includes 8 times, respectively at 03, 07, 10, 12, 14, 16, 19, and 23 Beijing Time. To meet the demands of data analysis, sounding-observed barometric pressure P (hPa), temperature T (°C), and relative humidity f (%) are respectively converted into altitude h(m), potential temperature θ (°C), and specific humidity q (g kg^{-1}).

The surface micrometeorological observation station is set up in Shuang Dunzi Gobi in the west of Dunhuang oasis. It is situated at 40°10′N, 94°31′E with the height of 1150 m above sea level, and its nearest distance to the edge of Dunhuang oasis is about 7 km. The observation site is in a flat Gobi. Observational data mainly include four layers (18, 8, 4, and 2 m) of mean of wind, temperature, and humidity, one layer (10 m) of wind direction and components of surface radiation and one layer (2.9 m) of fluctuations of wind speed, temperature, and humidity.The precisions of related instruments are mentioned in documents (Wang et al., 1992; Stull, 1991).

During the observational period, on June 4 and 12, there were two relatively stronger weather processes (a strong sandstorm occurred at dusk of the 4th and then there was a rainfall of 0.5 mm in the next morning; a rainfall of 1.8 mm appeared on the 12th).

3. Analysis method

The accuracy in the depth of atmospheric thermodynamic boundary layer is relatively difficult to determine, some technical problems still may be encountered even if the comparatively simple potential temperature profile is used for doing that, among which the crux is to identify atmospheric inversion layer exactly. According to the precision of observed data and the general characters of structure of boundary layer, we define that at nighttime a spatial range from the earth's surface upwards is the depth of stable boundary layer as long as its intensity of atmospheric inversion is in excess of 0.4°C/100 m; in the daytime a spatial range with an off-land atmospheric inversion in the same intensity is the inversion lid of convective boundary layer, namely the depth of entrainment layer; from inversion lid downwards to the earth's surface is the depth of atmospheric convective boundary layer.

4. Depth of thermodynamic boundary layer

4.1 *Observational results*

Convective boundary layer (CBL) develops most fully in sunny days, thus we first take a typical sunny day (May 29, 2000) as example to analyze the structure and depth of thermodynamic boundary layer.

Figure 1 shows characteristics of atmospheric potential temperature profile of daytime and nocturnal boundary layer in a typical sunny day (May 29, 2000) in Dunhuang region. As seen in Fig.1, in terms of shape the temperature structure of boundary layer is quite similar to the previous classic observational results (Wang et al., 1992). But the obvious distinction between them is that after 10:00 BT. The inversion lid of potential temperature profile is abruptly lifted to very high in the daytime, both nocturnal inversion range and diurnal quasi-equivalent potential temperature zone are evidently deeper than previous observational results (Stull, 1991), and the diurnal super-adiabatic lapse rate in near surface layer is also stronger than previous observational results (Garratt, 1992).

Figure 2 shows diurnal variation characteristics of the structure of atmospheric thermodynamic

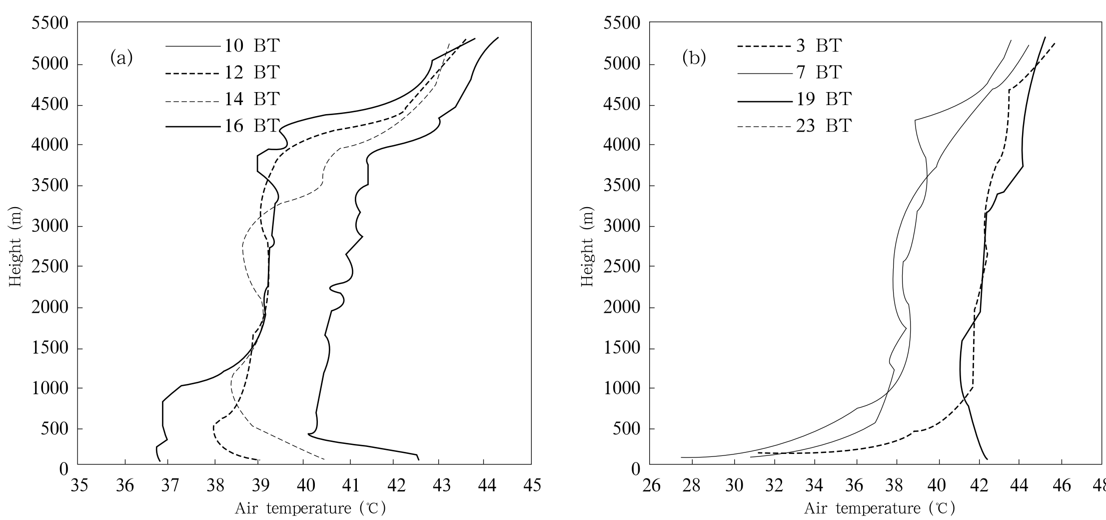

Fig.1. Characters of atmospheric potential temperature profile during boundary layer during the daytime (a) and nighttime (b) in a typical sunny day (May 29, 2000) in Dunhuang region.

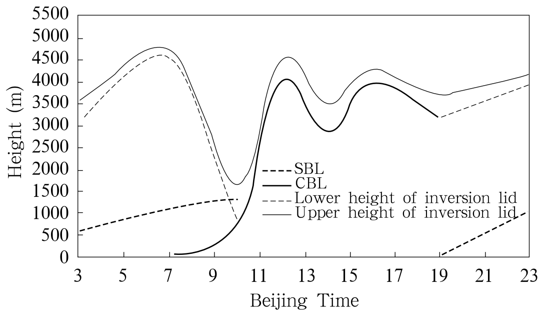

Fig.2. Diurnal variation characters of the depth of atmospheric thermodynamic boundary layer in a typical sunny day (May 29, 2000) in Dunhuang region.

boundary layer in a typical sunny day (May 29, 2000) in Dunhuang region. As seen that in the daytime, after 07:00 BT the convection in the ABL began to develop gradually till 10:00 BT, then it ascended suddenly, and reached a height over 3500 m at noon or so, from then on it maintained basically such a level (accompanied by slight fluctuation), and the thickest depth of CBL reached the altitude of 4150 m. At night the stable boundary layer began to develop from 19:00 BT and grew deepest until dawn, and exceeded a depth of 1000 m.

Table 1 gives concrete heights of various demarcations in the ABL on May 29, 2000 in Dunhuang region. Besides the height of ABL shown in Fig.2, it can also be found that the diurnal super-adiabatic lapse layer of atmospheric temperature in Dunhuang region is very thick whose height can be up to 800 m or so, and was never found in the past.

Table 1. Concrete heights (m) of various demarcations in the ABL on May 29, 2000 in Dunhuang region

Name	Beijing Time							
	3	7	10	12	14	16	19	23
Upper height of inversion lid	-	4750	1600	4520	3400	4150	3700	-
Lower height of inversion lid	3100	4450	750	4000	2950	4000	3100	4000
Height of CBL in daytime			750	4000	2950	4000	3100	
Height of stable boundary layer in nighttime	550	1000	1300				50	950
Height of super-adiabatic lapse rate layer			50	500	800	350		

The diurnal CBL, nocturnal stable boundary layer, and super-adiabatic lapse layer are so deep that beyond authors' expectation which were seldom mentioned in former references and textbooks. In view of these facts, this discovery has to be treated cautiously by authors.

In order to confirm the generality and truth of such a profound ABL, this paper analyzed the depth of CBL and stable boundary layer in entire observational period (May 29-June 9) of Dunhuang region, and gave daily variation curves of maximum values as shown in Fig.3. Clearly, during observational period, in all of 9 observing days, the maximum depths of effective thermodynamic convection boundary layer of other observing days are all in excess of 2000 m; daily maximum depths of 5 days are in excess of 3000 m whose frequency is up to 56%; 2 days among them are even in excess of 4000 m. Daily maximum depths of stable boundary layer maintain within 1000-1500 m, and the depths of all days are obviously extraordinary. Daily changes of CBL depth are very strong, and obviously related to weather process or clouds, the deepest CBL occurred in sunny days (May 29 and June 6), while that of the thinnest occurred in overcast days. This clearly shows that in

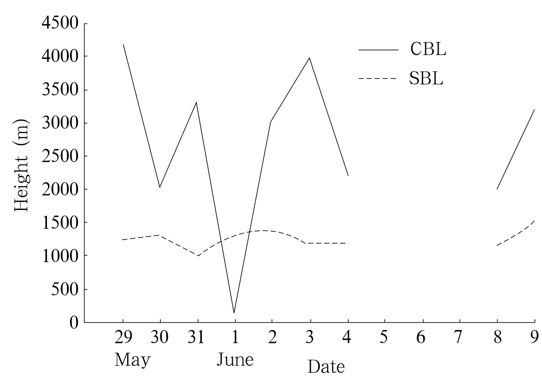

Fig.3. Daily variation of maximum depth of convective boundary layer and stable boundary layer from May 29 to June 6 in Dunhuang region.

summer of Dunhuang diurnal deep CBL and nocturnal stable boundary layer have universal properties, to a certain degree which has shown that the conclusion of deep ABL occurring in Dunhuang is considerably credible.

Generally speaking, the diurnal depth of CBL is 1000 m, and the nocturnal depth of stable boundary layer is 200 m. Although some researches (Su and Hu, 1987) found deeper CBLs observed in the Qinghai-Tibetan Plateau, the deepest of which is only 2200 m. After summarizing former observing results, Garratt (1992) considered that the maximum depth of CBL is generally lower than 2000-3000 m, while the maximum depth of stable boundary layer is generally lower than 400-500 m. For this sense, such a deep ABL is very extraordinary in Dunhuang region.

Observed diurnal depth of CBL were found up to 5000 m in low latitudes and desert regions such as Australia once when surface were heated strongly in summer (Wyngaard, 1980). Although experiment of this paper is done in middle latitudes, the observing facts are consistent with observational conclusions of low latitudes. It explains that physical mechanism of super-deep ABL works when the surface is heated enough in most sunny, dry surface desert areas. This is one of the most interesting problems of ABL, also a scientific problem deserves to be discussed.

Such a deep nocturnal depth of stable boundary layer in Dunhuang has never seen in references, which deserves us to discuss and analyze.

4.2 *Analysis of influencing factors*

The primary factors affecting ABL are surface heating and cooling, wind velocity condition, cloud, etc. As far as Dunhuang region is concerned, cloud's influence is rather slight, the first two of above factors are key causes for affecting the depth the of ABL generally.

Physical essence of CBL is that a hot bubble produced by the surface can directly hoist to a certain height, make heat mix abundantly, potential temperature distribute homogeneously in the range of hot bubble movement, and form a lid of inversion temperature. Hot bubble is the most primary turbulent eddy, and other small eddies are regard hot bubble as energies, thus hot bubble is the kernel of developing CBL. Active ability of hot bubble, namely lifting height directly decides the depth of CBL. In other words, depth of CBL is actually the embodiment of hot bubble's movement ability in vertical space. Primary motivity of forming hot bubble is the solar radiation flux, but that of supplying energy directly to hot bubble is the buoyancy flux (H_f) decided by surface sensible heat flux, which is generally expressed as (Zhao et al., 1991)

$$H_f = \frac{g}{T_v}\overline{w'\theta'_v}, \tag{1}$$

where g is the acceleration of gravity in m s^{-2}; T_v is the absolute virtual temperatures in K; $\overline{w'\theta'_v}$ is the sensible heat flux of kinematics in m s^{-1} K; and H_f is the buoyancy flux in m^2 s^{-3}. Production of great buoyancy flux depends on not only climatic background forcing such as strong illumination, but also surface properties such as weak surface evaporation and little soil heat capacity. Therefore it is possible to make more solar radiation fluxes change into the surface sensible heat flux of determining buoyancy flux.

Besides buoyancy flux can directly control the production and movement coverage of hot bubble, the environment of surrounding hot bubble can also indirectly affect the movement of hot bubble. Either wind speed shear caused by strong wind or wind direction shear caused by wind direction's sudden change can strengthen vertical mixing, increase hot bubble's lifting ability.

Therefore, theoretically speaking, CBL's developing height is commonly influenced by factors of solar radiation strength, surface character, and atmospheric dynamic environment. Among them the solar radiation strength and surface characters are crucial, and others are influencing factors.

Figure 4 is daily variations in the daily integration of surface total radiation flux, and the daily climax value of buoyancy flux from May 29 to June 9 in Dunhuang. As shown in Fig.4a, in most of time, the total solar radiation is well consistent with the depth of CBL in Fig.3, basically, strong radiation flux is consistent with deep CBL, but several days are not so, with the exception of May 29. The linear correlation

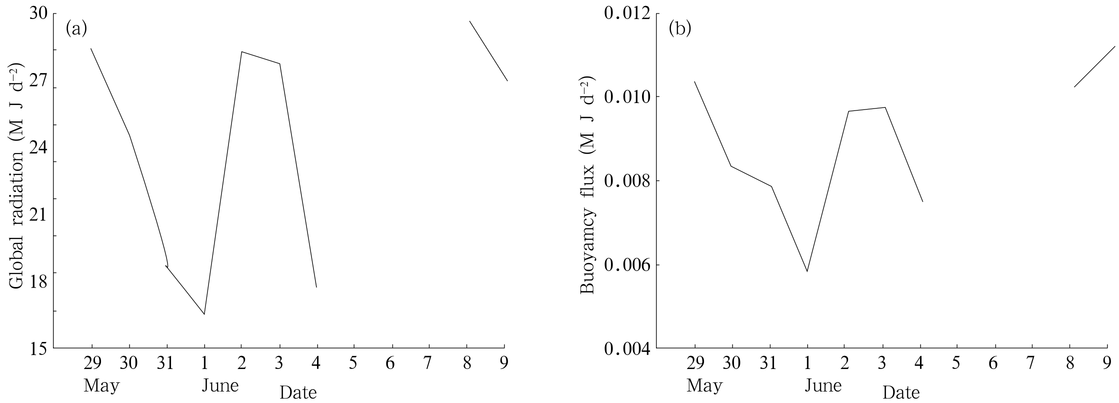

Fig.4. Daily variations in the daily integration of surface global radiation flux (a) and daily maximum value of buoyancy flux (b) from May 29 to June 9 in Dunhuang.

coefficient between total solar radiation and daily maximum depth of CBL is 0.33, with linear fitting relation

$$h_c = -689 + 139 \times R_f, \tag{2}$$

where h_c is the daily maximum depth of CBL in m, and R_f is the daily integration of total solar radiation in M J d^{-1}. This indicates the dependent relation of solar radiation with developing of CBL, while other factors' functions are not ignorable.

Comparison of observations indicates that the daily integration of global radiation is very great in most of time (figure omitted), their daily maximum values are approximate to 1000 W m^{-2} in most of days, and such a great global radiation flux is seldom found in other regions. In the same period, the global radiation observed in HEIFE region (Zou et al., 1992) is notably smaller, indicating that strong solar radiation flux is the climatic background of forming super-deep CBL.

As shown in Fig.4b, buoyancy flux is very great in most of time, which has mainly benefited from little heat capacity (Zhang et al., 2002a) and weak evaporation (Zhang et al., 2002b) over Gobi and desert in Dunhuang, thus most of solar radiation flux is converted into buoyancy flux and lays the energy basis of supporting CBL's development. As far as dynamic change is concerned, the corresponding relation of daily maximum value of buoyancy flux to depth of CBL is better than that of global radiation flux, and their change tendencies are almost accordant, meaning that bigger buoyancy flux must correspond to greater maximum depth of CBL. The linear correlation coefficient of them is 0.52, and linear fitting equation can be written as

$$h_c = -2101 + 532466 \times H_f. \tag{3}$$

However, comparison of Fig.4b and Fig.3 in detail indicates that there are still certain inconsistencies quantitatively. For example, the buoyancy flux of June 2 is so small that it is not suitable for its deep depth of CBL. It can be seen that buoyancy flux basically controls CBL's developing tendency, but dynamic environments such as wind velocity and wind direction have certain adjustment for developing CBL.

Figiure 5 shows the maximum east wind daily change in ABL from May 29 to June 9 in Dunhuang. Compared with Fig.3, it can be seen that change curves in daily maximum east wind of boundary layer and depth of CBL have accordant tendencies, bigger daily wind corresponds to deeper CBL. The reason is that the bigger the velocity is, the stronger the wind shear is, and the greater the help for hot bubble convection movement from the vertical mixing will be. Accordingly, hot bubble can be lifted higher and daily maximum depth of CBL is bigger, too. Linear correlation coefficient of them is 0.40, linear fitting equation is

$$h_c = -128 + 198 \times u_{\max}, \tag{4}$$

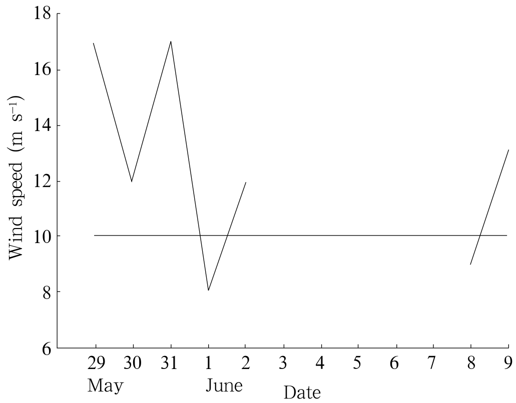

Fig.5. Daily change in the maximum east wind of ABL from May 29 to June 9 in Dunhuang.

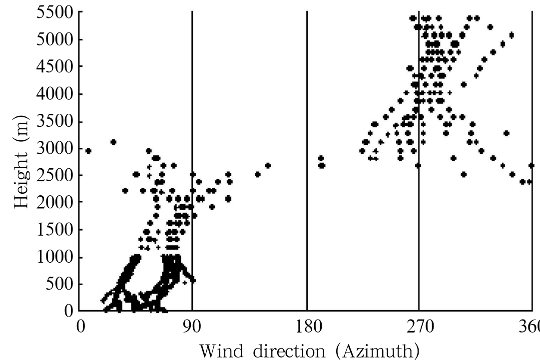

Fig.6. Spatial distribution of wind direction in boundary layer from May 29 to June 9 in Dunhuang.

where $u_{\max}$ is the daily maximum wind velocity of boundary layer, measured in m s^{-1}.

It is found from Fig.5 that the daily maximum wind velocity of boundary layer is totally great, seven of nine days' daily maximum east wind velocities are bigger than 10 m s^{-1}, with the biggest velocity near to 20 m s^{-1}, which is seldom seen in other regions. This big wind state may be rather advantageous to the dynamic environment condition of forming super deep CBL.

By comparing Fig.5 with Fig.3 quantitatively, change tendencies between daily maximum depth of CBL and daily maximum wind velocity of boundary layer also exist many inconsistentcies. Take the same example of June 2, this day's maximum wind velocity is very great, but its daily maximum depth of CBL is not big, and much less than that of May 29 which has the same velocity as that of June 2.

Comprehensive analysis reveals that daily climax value of buoyancy flux and daily maximum wind velocity of boundary layer have notable inter-compensation for influencing of maximum depth of atmospheric CBL. That is to say, the daily maximum depth of CBL is influenced by daily maximum velocity anomaly when it is not accordant with daily climax value of buoyancy flux, or influenced by daily climax value of buoyancy flux when it is not accordant with daily maximum velocity anomaly.

It is difficult to set up quantitative relation between CBL and wind direction shear, but the wind direction vertical distribution with height in Fig.6 revealed that the wind direction has obvious turning point near 2800 m, below it is east wind, and above it is west wind. Such an obvious and stable wind direction shear is seldom found before, this particular structure of wind direction shear could increase convective strength of hot bubble, and has some contribution to CBL's development.

It is found from above analyses that, the daily climax value of buoyancy flux and the daily maximum wind velocity of boundary layer are two basically independent quantities, however, both of them have notable influence on the daily maximum depth of CBL, so that a comprehensive parameter is set up that can indicate interactions of daily climax value of buoyancy flux and daily maximum wind velocity at the same time. Since the climax value of buoyancy flux expresses thermodynamic essence of heat convection and maximum wind velocity expresses dynamic environment of heat convection, thus a comprehensive parameter named as "thermodynamic parameter" is put forward and can be expressed as

$$\xi = H_f \times u_{\max}, \tag{5}$$

where ξ is the thermodynamic parameter, measured in m^3 s^{-4}.

Figure 7 illustrates the daily variation of thermodynamic parameter from May 29 to June 9 in Dunhuang. Clearly, thermodynamic parameter's corresponding relation with depth of CBL in Fig.3 is better

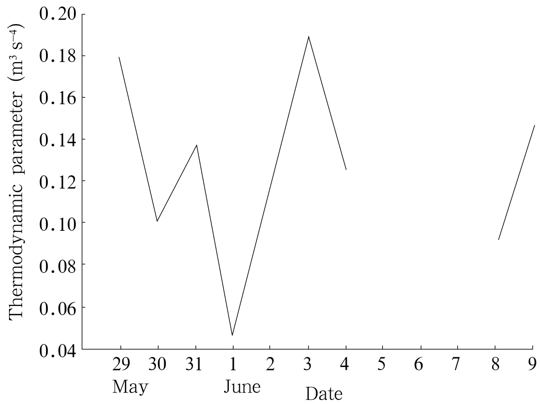

Fig.7. Daily variation of thermodynamic parameter from May 29 to June 9 in Dunhuang.

than that of daily climax value of buoyancy flux with depth of CBL in Fig.4b, not only their curve change tendencies are entirely consistent, but also their quantities fit very well, with the linear correlation coefficient bigger than 0.9. This indicates thermodynamic parameter basically includes physical process of affecting depth change of CBL.

Figure 8 gives illustration of buoyancy flux and atmospheric dynamic environment's influences on the depth development of CBL. It is seen that great buoyancy flux undoubtly makes surface atmospheric temperature higher than ordinary time, then a higher developing space of CBL must be needed in the same strength condition of inversion temperature top lid, its capital contribution to deepening CBL is to increase convective energy; while dynamic forcing caused by strong wind shear makes atmosphere weaken the strength of inversion temperature top lid of CBL through increasing entrainment, then in the same condition of surface atmospheric temperature CBL must extend higher, its capital contribution to deepening CBL is to increase the convective efficiency of buoyancy energy.

First, nocturnal stable boundary layer is undoubtly related to nocturnal surface radiation cooling, and certainly related to dynamic environment. In Gobi and desert regions, the sky is clear in most of time, the heat capacity of dry sand soil is very small, but the cooling speed of surface radiation is more quickly than that of others (Su et al., 1987), thus it can form a deeper inversion temperature layer. Meantime, strong wind velocity shear and direction shear theoretically increase the diffuse ability of boundary layer, extend vertical space range of radiation cooling influence, decrease the strength of atmospheric inversion temperature, deepen the coverage of atmospheric inversion, and form a profound nocturnal atmospheric stable boundary layer. Because nocturnal surface radiation cooling condition is much more stable than that of diurnal surface radiation heating, the daily change of nocturnal stable atmospheric boundary layer is not notable, the affecting principle resulting from radiation character and dynamic environment is similar to that of CBL given in Fig.8.

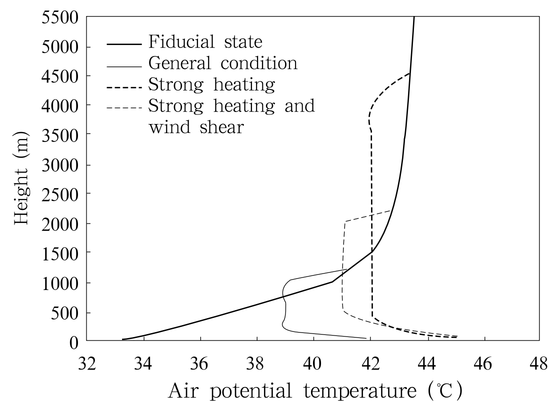

Fig.8. Illustration of strong surface buoyancy flux and strong wind shear's influences on development of CBL.

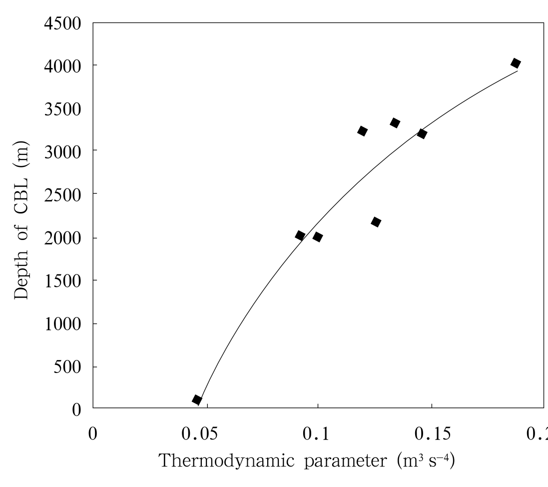

Fig.9. Fitting curve of daily maximum depth of CBL and thermodynamic parameter in Dunhuang.

As the relation of thermodynamic parameter with the depth of CBL is very good, the equation of estimating the depth of CBL may be set up by thermodynamic parameter. As a result, a fitting curve of the daily maximum depth of CBL and the thermodynamic parameter is given in Fig.9. It can be seen that their logarithm fitting relation is rather good, and the correlation coefficient is up to 0.934, with scatter deviation very small. Its fitting equation is

$$h_c = 8582.9 + 2770.8 \times \ln\xi, \tag{6}$$

where h_c is the daily maximum depth of CBL in m, and ξ is thermodynamic parameter.

Figure 10 depicts contrast between real observed data and the daily maximum depth of CBL calculated from Eq.(6) during May 29 and June 9. It can be seen that real observed values are very approximate to the empirical curve, in most of time they are almost superposed. Figure 11 depicts relations between real observed values and daily maximum depth of CBL calculated from Eq.(6). Their correlation coefficient is up to 0.935, the standard deviation and systematical error are only 87 and 10 m, respectively, however, the height resolution of general sounding observation is within 50-100 m or so, therefore, the calculated result from empirical formula Eq.(6) is rather good.

Figure 12 depicts the dynamic change of the daily maximum depth of CBL calculated from Eq.(6) with daily climax sensible heat flux and daily maximum wind velocity. It can be seen that changes of CBL depth with both sensible heat flux and daily maximum wind velocity are very obvious. In general region, sensible heat flux in summer is often 200 W m^{-2} or so, and the supposed daily maximum wind velocity of boundary layer is 13 m s^{-1}, then the depth of CBL in Fig.11 is about 1000 m, which is consistent with ordinary height. In the experiment of HEIFE, sensible heat flux in summer is often 350 W m^{-2} or so (Hu et al., 1992), daily maximum wind velocity of boundary layer is generally 10 m s^{-1} or so, then the depth of CBL in Fig.11 is about 1800 m, which is basically consistent with observed data (Wang et al., 1994), and also indicates that fitting Eq.(6) is reasonable to a certain degree.

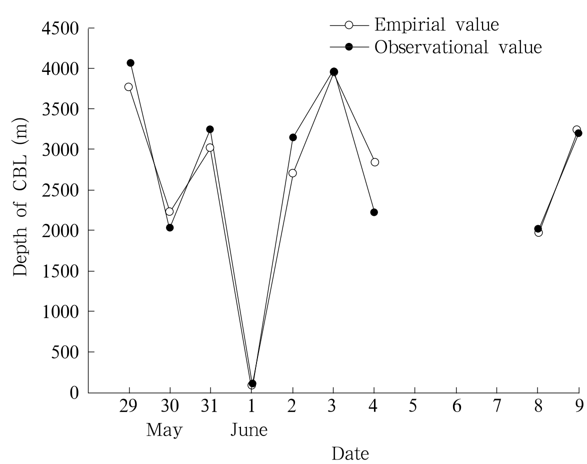

Fig.10. Comparison of observed data with the daily maximum depth of CBL calculated from Eq.(6) during May 29 to June 9.

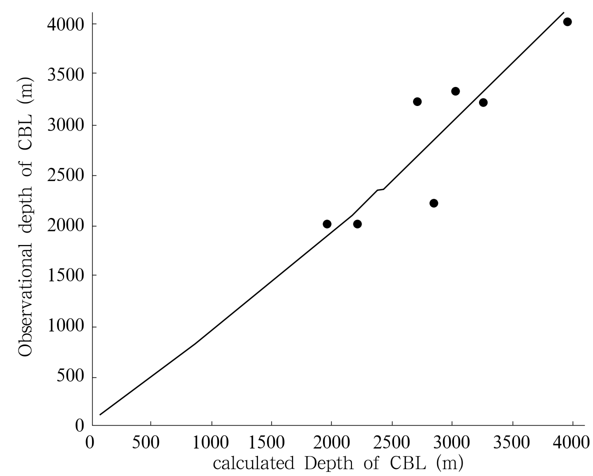

Fig.11. Relations between observed values and daily maximum depth of CBL calculated from Eq.(6).

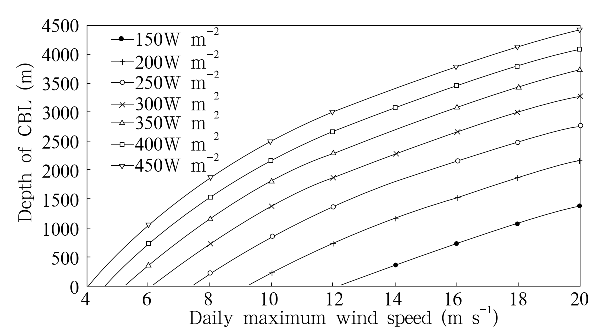

Fig.12. Dynamic change of the daily maximum depth of CBL calculated from Eq.(6) with daily climax sensible heat flux and daily maximum wind velocity.

As a result, we can obtain a physical frame of developing super CBL (Fig.13). In Fig.13 we can know that the forming of super CBL is not only determined by intensity of the solar radiation and surface characters, but also influenced by other factors.

5. Conclusions and discussions

The depth of ABL in Dunhuang is obviously more special than that of other areas. In daytime, most of the depths of CBL are in far excess of previous observed results in other areas, and its highest of daily maximum depth is almost up to 4000 m; the depths higher than 3000 m are general, and the number of days is almost half; except strong weather processes, in other time depths of ABL are higher than 2000 m. Almost the daily maximum depths of stable boundary layer are basically higher than 1000 m, generally, they maintain within a range of 1000 to 1500 m, depths of all days are notably deeper than that of previouly observed.

There are many factors affecting the depth of thermodynamic boundary layer. As far as CBL is concerned, hot bubble convective motion is the most key process, buoyancy flux is the energy basis of hot bubble convective motion, and the dynamic condition formed by wind velocity and direction shear is the main environment factor influencing hot bubble convective motion. Capital factors affecting the depth of CBL are solar radiation flux, surface property, dynamic environment, etc. In desert region strong solar radiation, weak surface evaporation and small soil heat capacity have created all the beneficial conditions for

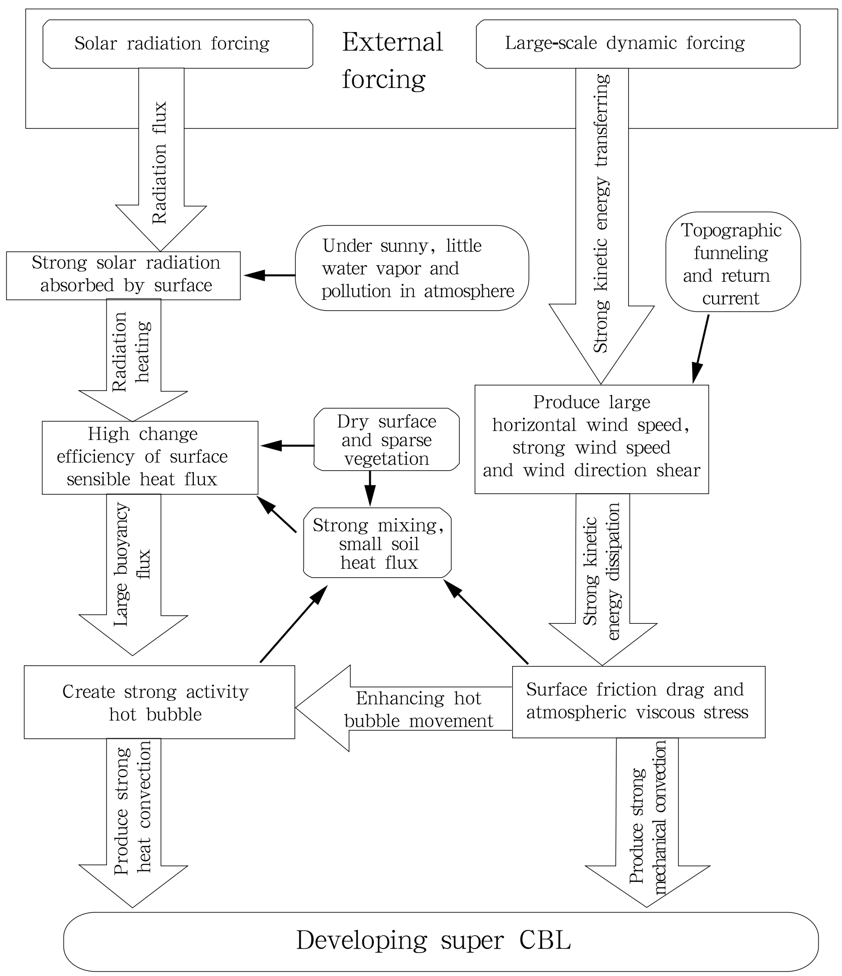

Fig.13. Forming mechanism of super CBL.

producing this area's super buoyancy flux altogether. Super buoyancy flux further has founded the energy basis of developing super deep CBL. Meantime, strong wind velocity and direction shear have increased the convective efficiency of buoyancy flux, and created good dynamic environment for favoring heat convection development of boundary layer. As far as nocturnal stable atmospheric boundary layer is concerned, in desert region the surface radiation is much more quickly than that of others, and can form a profound inversion temperature layer; favorable dynamic environment such as strong wind shear can increase the diffuse ability of boundary layer, and further extend the influence range of radiation cooling, then form the super nocturnal stable atmospheric boundary layer. Since nocturnal surface radiation cooling conditions are more stable than diurnal surface radiation heating conditions, the daily changes of nocturnal stable atmospheric boundary layer are more stable than that of diurnal CBL.

Daily maximum depth of CBL has obvious relations with both daily maximum value of buoyancy flux and daily maximum wind velocity, but their individual relation with daily maximum depth of CBL is not good. On the other hand, a thermodynamic comprehensive parameter combined by daily maximum value of buoyancy flux and daily maximum wind velocity can rather entirely express physical factors affecting atmospheric CBL, and it has very good correlation with daily maximum depth of CBL, with correlative coefficient of 0.934, and a good fitting equation is given by the thermodynamic parameter. The roughly estimated results are rather reasonable by using Eq.(6) which may be used to estimate the depth of CBL in similar regions.

The factors influencing ABL are rather complex, the proofs of so profound ABL found in this paper are also not sufficient. This important scientific problem will be continuously discussed through further observations and numerical models in the future.

Acknowledgments. The authors would like to thank Hou Xuhong, Hou Ping, Hu Zeyong, Nie Yanjiang, and Gao Hongchong for their helps of observing or collecting data, and also express gratitude particularly to Academician Huang Ronghui and Prof. Hu Yinqiao for their helpful discussions during preparation of this paper.

REFERENCES

Garratt, J. R., 1992: *The atmospheric boundary layer.* Cambridge University Press, Cambridge, 316.

Hu Yinqiao, Yang Xuanli, and Zhang Qiang, 1992: The characters of energy budget on the Gobi and desert surface in Hexi Region. *Acta Meteorologica Sinica*, **6**(1), 82-91.

O'Brien, J. J., 1970: A note on the vertical structure of eddy exchange coefficient in the planetary boundary layer. *J. Atmos. Sci.,* **27**, 1213-1215.

Pan Tao, Hu Yinqiao, and Ling Peishun, 1992: Primary analysis on wind field structure sounding of Huayin area with Doppler radar. *Plateau Meteorology*, **11**(4), 335-343. (in Chinese)

Stull, R. B., 1991: *Introduction to Boundary Layer Meteorology.* China Meteorological Press, Beijing, 107.

Su Congxian, Hu Yinqiao, and Zhang Yongfeng, 1987: Small climate characters of oasis in Hexi region and "Cold island". *Chinese J. Atmos. Sci.*, **11**(4), 390-396. (in Chinese)

Su Congxian and Hu Yinqiao, 1987: Structure of planetary boundary layer over oasis cold island. *Acta Meteorologica Sinica*, **45**(3), 322-328. (in Chinese)

Tennekes, H., and A. G. M. Driedonks, 1981: Basic entrainment equations for the atmosphereic boundary layer. *Bound. Layer Meteor.*, **20**, 515-513.

Vogelezang, D. H. P., and A. A. M. Holtslag, 1996: Evaluation and model impacts of alterative boundary-layer height formulations. *Bound. Layer Meteor*, **81**, 245-269.

Wang Jiemin, Cui Tiemin, and Tamakawa Ichiro, 1992: One turbulence real time process system of collecting data. *Plateau Meteorology*, **11**(4), 451-490. (in Chinese)

Wang Junqin, Hu Yinqiao, Chen Jiayi, et al., 1994: Some structure characters of boundary layer in HIEFE region. *Plateau Meteorology*, **13**(3), 299-306. (in Chinese)

Wyngaard, J. C., 1980: *Workshop on the Planetary Boundary Layer.* American Meteorological Society, Boston, MA, 322 pp.

Zhang Qiang and Hu Yinqiao, 1992: Observational errors of instrumental precision in "Zhong Fang" minimeteorology tower of "HEIFE". *Plateau Meteorology*, **11**(4), 460-469. (in Chinese)

Zhang Qiang, Wei Guo'an, and Huang Ronghui, 2001: The bulk transfer coefficients of the atmospheric momentum and sensible heat over desert and Gobi in arid climate region of Northwest China. *Science in China* (Series D), **31**(9), 783-792. (in Chinese)

Zhang Qiang, Cao Xiaoyan, Wei Guo'an, and Huang Ronghui, 2002a: Observation and study of some key parameters of land surface process of Gobi in arid region. *Advances in Atmospheric Sciences,* **19**(1), 1-14. (in Chinese)

Zhang Qiang, Wei Guo'an, and Huang Ronghui, 2002b: Oasis affect on atmospheric water circulation of near desert-data analysis of Dunhuang experiment. *Progress in Natural Science*, **12**(2), 195-200. (in Chinese)

Zhang Qiang and Cao Xiaoyan, 2003: The influence of synoptic conditions on the averaged surface heat and radiation rudget energy over desert or Gobi. *J. Atmos. Sci.*, **27**(2), 247-254. (in Chinese)

Zhao Ming, Miao Manqian, and Wang Yanchang, 1991: *Textbook of Boundary Layer Meteorology.* China Meteorological Press, Bejing, 33-37. (in Chinese)

Zhou Mingyu, Xu Xiangde, Bian Lin'gen, et al., 2000: *Dynamic study and observational analysis of atmospheric boundary layer in Qinghai-Tibetan Plateau.* China Meteorological Press, Beijing, 68-72. (in Chinese)

Zou Jiling, Hou Xuhong, and Ji Guoliang, 1992: Primary analysis on solar radiation characteristics in late summer in HIEFE region. *Plateau Meteorology*, **11**(4), 381-388. (in Chinese)