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To cite this article: Anran Li *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **300** 032072

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Analysis of Turbulent Characteristics of Sheared Convective Boundary Layer under Different Shear and Potential Temperature Gradients

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Abstract. Effects of shear and potential temperature gradient on the formation mechanism and turbulence characteristics of the sheared convective boundary layer are studied through Large-Eddy Simulation (LES) experiments. Four cases with different velocity difference ΔU of 1.5ms^{-1} and 3.0ms^{-1} and different potential temperature gradient Γ_θ of 0.006Km^{-1} and 0.015Km^{-1} were conducted in the horizontal homogeneous atmospheric convective boundary layer of $6000\text{m} \times 6000\text{m} \times 2000\text{m}$. The results show that the formation of the entrainment layer is affected integrally by the horizontal shear effect and the vertical buoyancy effect, in which turbulence shows strong anisotropy and intermittent characteristics, wherein the mixed layer is dominated by stable small eddies, and the entrainment layer by strip-shaped large eddies. Compared with the pure buoyancy boundary layer, the entrainment flux ratio A_f is $0.176 \sim 0.385$, and the height of the entrainment layer z_i is shifted to the side with bigger velocity (U_2). ΔU promotes entrainment and Γ_θ inhibits, especially for the upper limit of the entrainment layer h_2 . Obviously, the shear-shelter entrainment phenomenon appears under the weak shear and strong potential temperature gradient.

1. Introduction

Sheared Convective Boundary Layer (SCBL) is a turbulent boundary layer underlying the atmosphere close to the ground by shear and buoyancy. The flow field in the SCBL is much more complicated, and the exchange of material and heat between the upper and lower atmosphere are inhibited by the "covering" effect of the entrainment layer. It is difficult for the material and heat in the mixed layer to penetrate into the free atmosphere, and vice versa. The study of SCBL flow field characteristics has important scientific significance for atmospheric science and environmental and engineering applications, for example, improving the accuracy of numerical weather prediction [1] [2], predicting the spread of pollutants in the atmosphere or rivers [3], and so on.

Due to the existence of shear effect, the conclusion of the entrainment characteristics of the convective boundary layer based on pure buoyancy is deviated, which leads to the entrainment



phenomenon not be well explained. In this paper, LES simulation method is conducted to study the turbulence characteristics of SCBL. By analysing the variation of the characteristic parameters of the flow field, the formation mechanism of the entrainment layer and the influence of shear and potential temperature gradient on the flow field are studied.

2. Physical model and LES

In this paper, the calculated domain is a cloudless dry but horizontal homogeneous atmospheric space (6000m×6000m×2000m in the x, y and z direction) with a flat underlying surface with constant vertical heat flux, which is similar to the calculation domain used by Kim (2006) [4]. The height of the entrainment layer z_i is initialized to 1000m, below which the potential temperature θ_0 is set 300K, and the upper temperature gradient is Γ_θ . The initialization data is shown in Table 1.

The turbulence calculation model uses LES to accurately capture the motion equations of all turbulence scales above the characteristic eddy scale, thereby capturing large-scale effects and quasi-order structures during unsteady, no equilibrium processes.

Table 1. Team list of simulated cases in different combinations of U and Γ_θ

case	$\overline{w'\theta'} _s$ (K·ms ⁻¹)	U_1 (ms ⁻¹)	U_2 (ms ⁻¹)	Γ_θ (Km ⁻¹)
case-1	0.10	3	4.5	0.006
case-2	0.10	3	6	0.006
case-3	0.10	3	4.5	0.015
case-4	0.10	3	6	0.015

Remark: $\overline{w'\theta'}|_s$ is the heat flux of the underlying surface, U_1 and U_2 represent the component of velocity in mixed layer and the free atmosphere respectively, and Γ_θ is the potential temperature gradient of the free atmosphere.

The quasi-steady calculation time of all cases in this paper is 85min, which satisfies the empirical requirements of calculation time $t > 6t_*$ to ensure the adequacy of turbulent mixing [5]. Characteristic time scale $t_* = z_i/w_*$, where z_i is the height of the entrainment layer in which buoyancy flux $\overline{w'\theta'}$ is the negative maximum, and characteristic convection velocity scale is $w_* = \left[\frac{g}{\theta} z_i \overline{w'\theta'}|_s \right]^{1/3}$, where superscript is the fluctuation of the parameter and the subscript is the location: s denotes the underlying surface. The main time-average parameters obtained from the calculated results are shown in Table 2 below. h_1 and h_2 are the upper and lower limits of the entrainment layer where the $\overline{w'\theta'}$ reaches zero with the increasing of the height; δh is the entrainment layer thickness, $\delta h = h_2 - z_i$; $\Delta\theta$ is the temperature jump value in entrainment layer; u_* is the friction characteristic velocity, $u_* = \sqrt{-\overline{u'w'}|_s}$; and A_f denotes the buoyancy flux ratio, $A_f = -\overline{w'\theta'}|_{z_i} / \overline{w'\theta'}|_s$.

Table 2. LES simulated parameters in association with entrainment.

case	ΔU (ms ⁻¹)	h_1 (m)	z_i (m)	h_2 (m)	δh (m)	$\Delta\theta$ (K)	u_* (ms ⁻¹)	w_* (ms ⁻¹)	A_f
case-1	1.5	962	1118	1350	232	1.395	0.277	1.42	0.176
case-2	3	936	1152	1410	258	1.72	0.28	1.425	0.212
case-3	1.5	868	1103	1192	89	1.58	0.276	1.398	0.202
case-4	3	854	1076	1203	127	1.805	0.277	1.393	0.385

3. Formation mechanism of entrainment

3.1. Buoyancy effect on the entrainment layer

Lenschow (1980) [6] and Young (1988) [7] carried out related experimental researches on the motion structure and characteristics of thermal bubbles, and Lamb (1978) [8] and Moeng (1989) [9] also used numerical simulation for the problems. However, their efforts did not lead to a consistent conclusion due to the lack of a definition of a clear physical meaning for the formation of thermal bubble and the neglect of a quantitative description of the spatial structure of the thermal bubble motion.

The isothermal surface can clearly express the shape and trajectory of the thermal bubble. Fig.1 shows the distribution of the thermal bubble with a temperature of $\theta_0 + 0.5$ °C in the case-1. From the figure, it can be seen that the heating effect of the underlying surface increases a part of adjacent atmospheric temperature and locally generates thermal bubble moving upward by the net buoyancy from temperature differences with the surrounding. During the rise of the thermal bubble, the volume will decrease for the heat exchange with the ambient atmosphere along the process, so the thermal bubble has a shape of “small top and big bottom”.

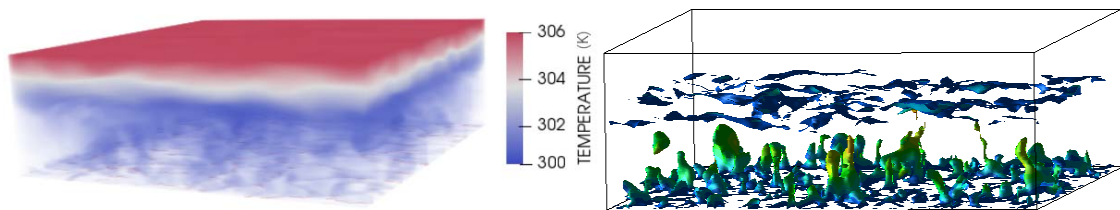


Figure 1. Temperature contour and thermal bubbles distribution at $\bar{\theta} = \theta_0 + 0.5$ in the calculated domain of case-1

In SCBL, the thermal bubble diameter in the x direction (wind direction) is slightly larger than in y direction (spanwise direction) due to the influence of lateral wind shear. Fig.2 shows a vertical velocity contour of the orthogonal interfaces located in the center of the calculation domain. The updrafts or downdrafts in the y=3000m interface are concentrated, while relatively interlaced and scattered in x=3000m interface. The existence of this phenomenon is mainly caused by the flow inertia in the flow direction, which makes the scale of the turbulent eddy in x direction larger than in y direction and the flow field anisotropy.

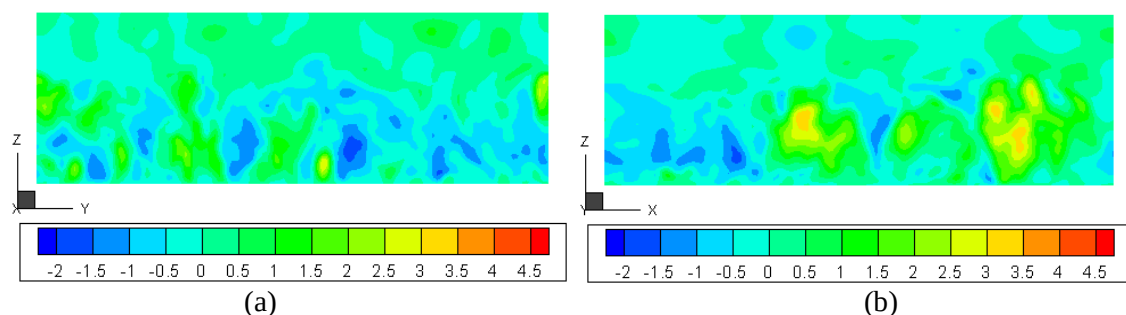


Figure 2. Z component velocity contour in orthogonal interfaces of case-1. (a) interface at x=3000m; (b) interface at y=3000m

3.2. Shear effect on the entrainment layer

When the shear produced by velocity difference in the interface between the mixed layer and the free atmosphere exceeds the threshold of atmospheric static stability, the flow field will be unstable and the upper and lower layers of fluid are entrained and carried by each other under the action of viscosity

and shear, which lead to large-scale Kelvin-Helmholtz wave (K-H wave). Based on numerical simulation data, SI-WAN et al. (2002) [10] concluded that the instability of K-H wave is caused by the vertical shear stress of horizontal wind which promotes entrainment of the mixed layer and the free atmosphere. With the development of flow, the K-H wave is continually broken into small-scale turbulent eddies for the viscosity [11], and the free atmosphere is entrained into the mixed layer to form a stable entrainment layer [12] [13].

Fig.3 demonstrates a vorticity evolution in $y=3000\text{m}$ interface of the case-1 flow field throughout the whole computational process. Obviously, the development of flow can be divided into three stages with distinct characteristics: K-H eddy formation stage, K-H eddy instability stage, and stable turbulence stage. The process of K-H eddy formation costs limited duration, only accounting for about 1/5 of the whole process. The K-H eddy scale increases to a certain critical extent with the development of the flow, and the eddy begins to stretch and break in the flow direction for the fluid viscosity is insufficient to support the rotation of the eddy. The instability and break evolution of the K-H eddy takes up most of the process, which urges the quality and energy exchange between the upper and lower layers. Finally, a stable turbulent thin layer, i.e. entrainment layer, is formed.



Figure 3. Evolution of the turbulent vorticity in $y=3000\text{m}$ interface of case-1

3.3. Vorticity analysis

As shown in Fig.4 of the 0.01s^{-1} vorticity distribution in the case-1 of stable entrainment stage, the mixed layer is filled with small-scale vortices, the entrainment layer is mainly dominated by large-scale vortices, and the free atmosphere is advective. The turbulent energy cascade theory indicates that large-scale vortices, obtaining turbulent kinetic energy (TKE) from time-averaged flow by turbulent shear, are split into small vortices of different scales through viscous dissipation and dispersion processes, and then TKE is transferred to the small-scale vortices step by step until which is all dissipated by viscosity. The large vortices of the entrainment layer mainly are split into small vortices in the vertical direction, and stretch or breaks into the small vortices and re-bonds to form a strip-shaped thin layer-entrainment layer in the horizontal flow direction, which shield the exchange of material and energy between the free atmosphere and the mixed layer.

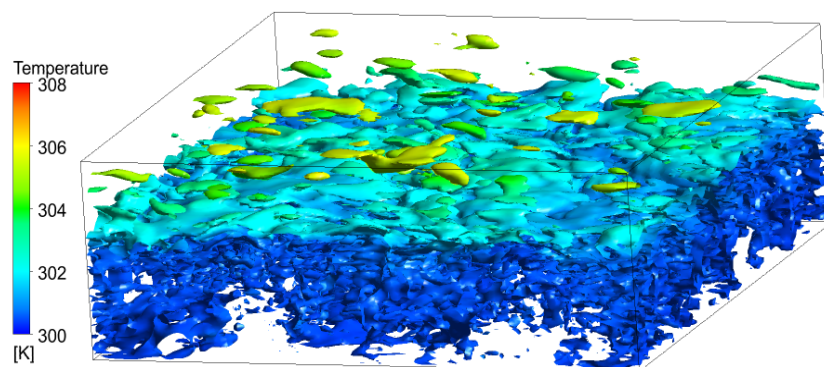


Figure 4. 0.01s^{-1} vorticity contour in case-1

Considering both vertical and horizontal effects, the macroscopic mechanism for the fluid turbulence are the result of the combined effects of velocity shear and potential temperature buoyancy, which are co-existent and co-acting during the turbulence development in the SCBL. In the horizontal direction, the wind velocity difference shear causes the generation and break of the K-H wave and the

entrainment of the upper and lower airflows; the thermal bubbles generated by the heating of the underlying surface in the vertical direction also promote entrainment by the ascending and descending in different layers.

Therefore, the occurrence of entrainment is rooted in the input heat flux of the underlying surface and the shear of the entrainment layer (and shear between underlying surface and the mixed layer, but the effect is so small that it is negligible), while the potential temperature difference inhibits the effect of entrainment.

4. Flow field parameters analysis

4.1. Velocity and potential temperature distribution

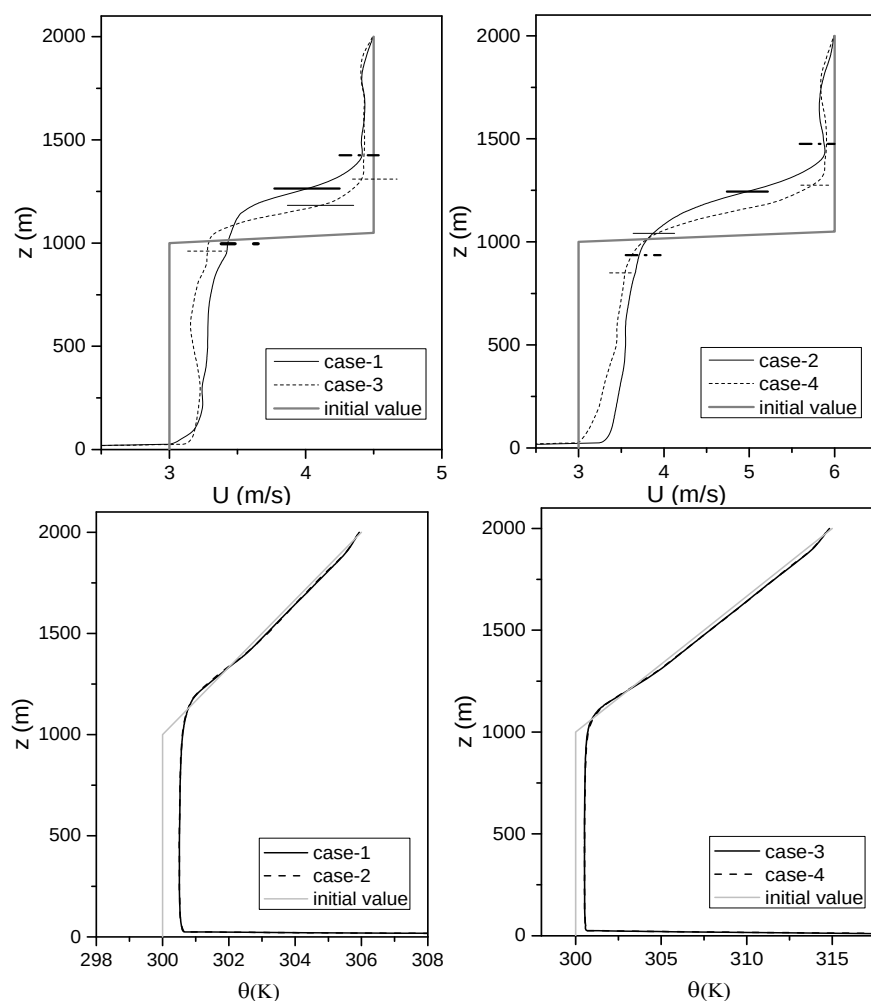


Figure 5. Profiles of x component velocity U and potential temperature θ . The lower and upper limits of the entrainment layer are marked by short dashed horizontal lines, and the height of entrainment layer is marked by short solid line.

It can be seen from the U -profile and θ -profile in Fig.5 that z_i is higher than the initial value of 1000m under the same underlying surface heat flux condition, that is, the height of the entrainment layer is shifted toward the side with higher velocity ($U_2 > U_1$). Since $U_2 > U_1$, the eddy rotates horizontally from the free atmosphere to the mixed layer in a clockwise direction, leading to the upper air is entrained more than the lower; on the other hand, the free atmospheric density is smaller than

that of the mixed layer in the vertical direction ($\theta_2 > \theta_1$), so the height of the wave peak is bigger than that of wave valley when the thermal bubbles oscillate at the equilibrium position in the entrainment layer, causing the height of the entrainment layer to move up. That is to say, from the two aspects of shear and buoyancy effects, the mass composition of entrainment layer is larger from the relatively higher velocity side.

Information from the U -profile shows that z_i , h_1 and h_2 of the cases where Γ_θ is 0.015Ks^{-1} are lower than that of the cases where Γ_θ is 0.006Ks^{-1} under the same limits of ΔU , indicating that the temperature gradient has an inhibition effect on entrainment process, and the influence on the upper limit of the entrainment layer is somewhat larger.

Information from the θ -profile shows that the two potential temperature curves with different ΔU and same Γ_θ are basically coincident and the difference in parameter evolution trend is not obvious, indicating that θ is not influenced significantly by ΔU under the same Γ_θ , because the influence of θ on the vertical motion of thermal bubbles is mainly limited by the input heat flux from the underlying surface.

4.2. Turbulence intensity and TKE

As shown in Fig.6, there are two extremums of I_x and I_y in the mixed layer near the underlying surface and entrainment layer, consistent with the trend of the shear stress τ_{xy} in these regions, so the shear stress is the main cause of turbulence. According to the trends of TKE_x and TKE_y in the mixed layer, the TKE produced by shear in the underlying surface is dissipated quickly without obvious effect on the upper mixed layer, which is in accordance with the conclusion of R Conzemius (2007)[14].

Mainly because buoyancy and shear accelerates the thermal bubbles production and movement in the lower mixed layer, $\overline{w'^2}$ increases, but the shear in the underlying surface disappears in a short height and the buoyancy decreases when leaving the thin layer near ground, which make the I_z and TKE_z gradually increase in the mixed layer and get the maximum at the height of $0.4z_i$. The trend is the same as that of τ_{xz} and τ_{yz} , indicating that shear near the underlying surface and buoyancy promote the development of vertical turbulence. I_z and TKE_z decrease gradually above $0.4z_i$, inconsistent with the change of shear components in this direction, which increase above $0.8z_i$. Although τ_{xz} and τ_{yz} are affected by the entrained shear at $0.8A \sim 1.0A$ to increase, the flow is in control of the negative buoyancy inhibiting the turbulence which have a greater effect on the I_z and TKE_z and make them decrease continuously.

Therefore, it can be drawn from above analysis that the turbulence in the mixed layer is mainly caused by the shear and the buoyancy of underlying surface, and the shear stress in the middle and lower part of the mixed layer is the main cause of turbulence; the closer to the entrainment layer, the more the buoyancy effect is affected. Obviously, the entrainment layer is affected by the negative buoyancy, which inhibits the occurrence of turbulence, and TKE has a downward trend.

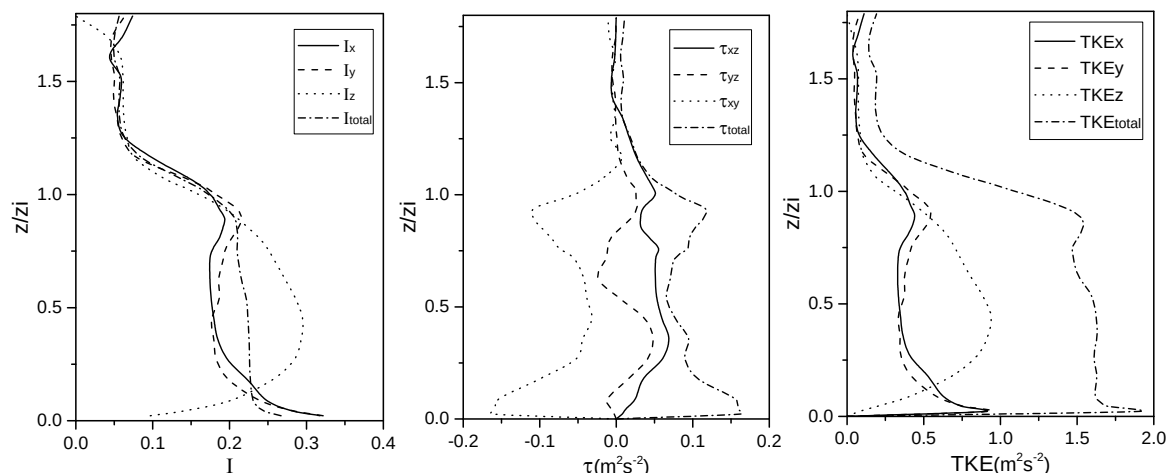


Figure 6. Profiles of vertical average turbulence intensity I , Reynolds stress τ and turbulence kinetic energy TKE

4.3. Entrainment height z_i and entrainment flux ratio A_f

By analyzing the main flow field data in Tab.2 and Fig.7, z_i is 1118 m and the upper limit height h_2 is 1350 m in case-1, which are bigger than the corresponding parameters value of 1103m and 1192m in case-3 with the same $\Delta U = 1.5 \text{ ms}^{-1}$, and the same is true for the comparison between case-2 and case-4. The higher Γ_θ makes the smaller z_i and δh , but has little effect on h_1 , indicating that the inhibition of potential temperature stratification on entrainment is mainly on the higher velocity side (U_2).

Comparing data in case-1 and case-2, δh increases by 26m where Γ_θ is 0.006 Km^{-1} , and by 38m comparing case-3 and case-4 where Γ_θ is 0.015 Km^{-1} identically, revealing that shear promoted the material exchange between upper and lower layers to lead the thickness of entrainment to increase. However, the larger change of Γ_θ , but the greater the change of δh within the same interval of ΔU from 1.5 ms^{-1} to 3.0 ms^{-1} , not showing the inhibitory effect on the entrainment. The reason maybe that the turbulent eddies generated by shear at the interface are blocked and dissipated untimely by viscosity in case-3 with strong potential temperature gradient and weak shear effect, and shear-sheltered entrainment appears [15]. Hunt and Durbin (1999) [16] proposed that shear in the entrainment layer inhibits entrainment rather than enhances it in some cases, and the shear-sheltered phenomenon occurs when the eddies prevent the rising thermal plume, thereby reducing the extent to which they can penetrate the entrainment layer. Conzemius and Fedorovich (2006) [17] have found evidence of this phenomenon, but the evidence is only inferred from the reduced general entrainment rate. So far, no direct evidence of shear-sheltered entrainment has been found based on measurements of local turbulence dynamics.

The entrainment flux ratio A_f is defined as the ratio of the heat flux at z_i to the heat flux on the underlying surface, $A_f = -(\overline{w'\theta'})_{z_i} / (\overline{w'\theta'})_s$. It was recognized that $A_f = 0.2$ is applicable to a wide range of cases in the pure convective boundary through field observations, water tank experiments and numerical simulations [18][19][20]. The values of A_f in case-1 and case-3 with weak shear effect are 0.176 and 0.202, while those in case-2 and case-3 with strong shear effect are 0.212 and 0.385, respectively. A_f increases with the shear strengthening, mainly because the TKE produced by shear effect is partly used for entrainment, making the minimum negative buoyancy flux $\overline{w'\theta'}_{z_i}$ shift to the left.

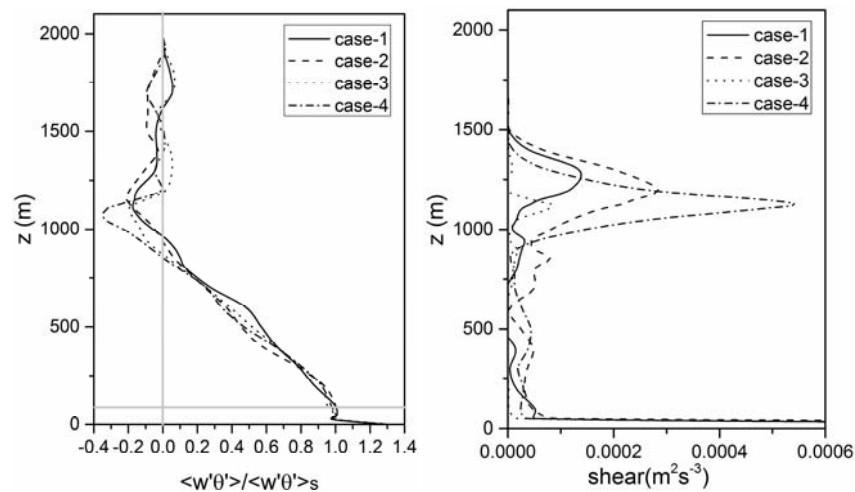


Figure 7. Evolution of the buoyancy production of TKE and shear production of TKE

5. Conclusion

The formation of entrainment in SCBL is mainly affected by horizontal shear effect and vertical buoyancy effect. The shear effect at entrainment layer strengthens the generation and breakup of K-H wave, and then promotes entrainment. And the vertical motion of the bubbles strengthens the material and energy exchange between the upper and lower airflows and promote the entrainment process. However, the temperature gradient inhibits the entrainment, which is mainly manifested in the inhibition the upper part of the entrainment layer.

The SCBL flow field is dominated by small eddy turbulence in the mixed layer, and tends to be isotropic and weak intermittent. While in the entrainment layer, the flow field distributed strip-shaped large eddies with strong anisotropic and intermittent characteristics.

With the same ΔU , the height and thickness of the entrainment layer decreased in cases with Γ_θ of 0.006Km^{-1} compared cases of 0.015Km^{-1} , indicating that the potential temperature gradient inhibited the entrainment, especially for the relatively higher velocity side (U_2). However, in the same interval of ΔU (1.5ms^{-1} to 3ms^{-1}), the thickness of entrainment layer increases with the higher potential temperature gradient (0.015Km^{-1}), mainly due to shear-shelter entrainment under the condition of strong potential temperature gradient and weak shear.

The calculated values of entrainment flux ratio A_f are 0.176-0.385 in the ΔU and Γ_θ ranges of this paper. However, due to shear-shelter entrainment under strong potential temperature gradient and weak shear conditions, A_f is slightly lower than the empirical value of pure buoyancy convection (0.2), but in other cases, A_f is greater than 0.2, indicating that shear promotes entrainment.

Additionally, entrainment is the result of shear and buoyancy combined interaction, but shear and buoyancy are located in different dimensions, and they interact with each other in a three-dimensional way. Therefore, it is necessary to further study the interaction mechanism between them, to clearly explain the formation mechanism of entrainment and shear-shelter phenomenon. The scaling relationship between the entrainment flux ratio, the height of the entrainment layer and the shear and temperature gradients, as well as the proportion of the shear effect used to promote entrainment, should be further studied.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (No.11662021), and got help from Computational Fluid Dynamics Laboratory of the Solar Energy

Research Institute of Yunnan Normal University. The first author of this paper thanks all those who provided help.

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