ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 22, NO. 1, 2005, 114–121

Parameterization for the Depth of the Entrainment Zone above the Convectively Mixed Layer

SUN Jianning*[1] (孙鉴泞), JIANG Weimei[1] (蒋维楣), CHEN Ziyun[1] (陈子赟), and YUAN Renmin[2] (袁仁民)

[1]*Department of Atmospheric Sciences, Nanjing University, Nanjing* 210093

[2]*Department of Earth and Space Sciences, University of Science and Technology of China, Hefei* 230026

(Received 22 December 2003; revised 1 June 2004)

ABSTRACT

It has been noted that when the convective Richardson number Ri^* is used to characterize the depth of the entrainment zone, various parameterization schemes can be obtained. This situation is often attributed to the invalidity of parcel theory. However, evidence shows that the convective Richardson number Ri^* might be an improper characteristic scaling parameter for the entrainment process. An attempt to use an innovative parameter to parameterize the entrainment-zone thickness has been made in this paper. Based on the examination of the data of water-tank experiments and atmospheric measurements, it is found that the total lapse rate of potential temperature across the entrainment zone is proportional to that of the capping inversion layer. Inserting this relationship into the so-called parcel theory, it thus gives a new parameterization scheme for the depth of the entrainment zone. This scheme includes the lapse rate of the capping inversion layer that plays an important role in the entrainment process. Its physical representation is reasonable. The new scheme gives a better ordering of the data measured in both water-tank and atmosphere as compared with the traditional method using Ri^*. These indicate that the parcel theory can describe the entrainment process suitably and that the new parameter is better than Ri^*.

Key words: convectively mixed layer, the depth of the entrainment zone, capping inversion layer, parameterization scheme, parcel theory

1. Introduction

The simplest zero-order models of mixed-layer growth assume that turbulence is sufficient to maintain a layer of nearly uniform potential-temperature profile, capped by an entrainment zone that is represented by a step-like potential-temperature jump. The entrainment zone constitutes the outermost portion of the mixed layer where non-turbulent air is entrained but not yet fully blended into the mixed layer. The assumption of uniform potential temperature profile is well in agreement with measurements. Nevertheless, the hypothesis of the step-like potential temperature jump is not yet evident. The thickness of the entrainment zone is typically 30% of the mixed layer, and can even reach a depth comparable with the mixed layer itself.

The scheme adopted in this paper is the so-called first-order model (Deardorff, 1979). It is portrayed in Fig. 1. The turbulence is assumed to be sufficiently intense to maintain a uniform distribution of potential temperature θ within the mixed layer up to the height h_0. The air immediately above constitutes an entrainment zone, of thickness Δh, consisting of very stably stratified but turbulent air with a potential-temperature jump $\Delta\theta$. The mixed-layer height h is

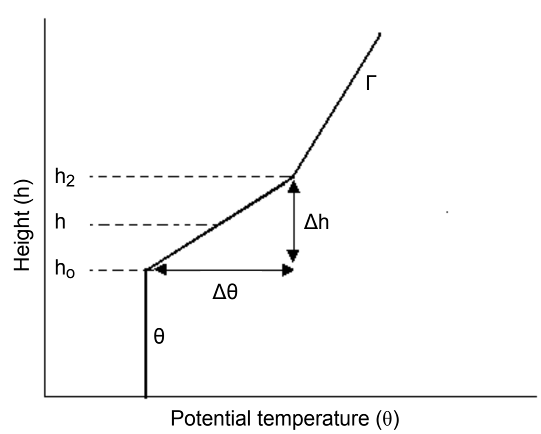

Fig. 1. Sketch map of potential-temperature profile.

*E-mail: jnsun@nju.edu.cn

approximately in the middle of the entrainment zone. Above the upper edge of the entrainment zone, h_2, is the stable free atmosphere with a lapse rate Γ.

One of the first attempts to parameterize the entrainment-zone thickness (Betts, 1976) assumed it to be proportional to the mixed-layer depth. A more physical parameterization is based on the so-called parcel theory, where the depth of the entrainment zone is related to the extent to which a rising thermal overshoots its neutral buoyancy level and extends into the stable air aloft. The characteristic velocity of the rising thermal is assumed proportional to the usual convective velocity scale w_* that is obtained from bottom-up scaling. This leads to a dependence between the normalized entrainment-zone depth and a convective Richardson number Ri^* (Stull, 1973; Zeman and Tennekes, 1977; Mahrt, 1979), shown in relationship (1) or (2).

$$\Delta h \sim w_*^2 / \left(\frac{g}{T_0} \Delta\theta \right) , \tag{1}$$

$$\frac{\Delta h}{h} \sim Ri^{*-1} . \tag{2}$$

Here,

$$Ri^* = \frac{g}{T_0} \Delta\theta h / w_*^2 ,$$

g is the gravitational constant, T_0 is a bulk temperature, $\Delta\theta$ is the potential temperature jump across the entrainment zone, Δh is the depth of the entrainment zone, h is the mixed-layer height, w_* is defined as

$$w_*^3 = \frac{g}{T_0} \overline{(w'\theta')_s} h$$

and $\overline{(w'\theta')_s}$ is the virtual kinematical heat flux at the surface.

By using the data measured during CIRCE (Central Illinois Rainfall Chemistry Experiment), Bores and Eloranta (1986) obtained a relationship as follows:

$$\Delta h = \alpha \cdot (w_*^2 / \frac{g}{T_0} \Delta\theta)^\beta , \tag{3}$$

where α is a constant which equals 38.41, and $\beta = 0.41$, which is not equal to 1 as in Eq. (1). It is worth noticing that Eq. (3) is not a proper relationship because the units of the two terms on both sides of the equation are not the same, although they can be balanced by the constant on the right-hand side. This means that α is not a dimensionless constant. It makes the physics of Eq. (3) ambiguous. Based on an energy-balance model, Boers (1989) found that the normalized depth of the entrainment zone depends on the convective Richardson number to the $-1/2$ power. This relationship improves the fitting of the data of Boers and Eloranta (1986), but not of Deardorff et al.'s (1980) laboratory experiment.

According to the data measured in a water tank, Deardorff et al. (1980) gave a relationship between the normalized depth of the entrainment zone and convective Richardson number:

$$\frac{\Delta h}{h_0} = \frac{1.31}{Ri^*} + 0.2 , \tag{4}$$

where h_0 is the height between the bottom of the entrainment zone and the surface. In a re-examination of his laboratory experiments, Deardorff (1983) suggested a $-1/4$ power relationship between normalized entrainment-zone depth and convective Richardson number.

Because of large differences among the results of various studies in which the convective Richardson number Ri^* is used to parameterize the entrainment-zone depth, it seems that the parcel theory is invalid (Boers and Eloranta, 1986; Boers, 1989; Gryning and Batchavarova, 1994). The poor agreement of both the atmospheric and laboratory data with parcel theory shows that other factors may be important for the entrainment. Since Ri^* is a characteristic parameter that is only suitable in the purely convective boundary layer, it cannot properly describe the complex convection in the planetary boundary layer driven by not only buoyancy but also wind shear. Maybe it is the convective Richardson number instead of the parcel theory that makes the perplexity in parameterization of the thickness of the entrainment zone. This problem is discussed in this paper. Furthermore, a new parameterization scheme for the entrainment-zone depth is proposed.

2. Analyses on the parameterization of entrainmentzone depth

2.1 *About the parcel theory*

The entrainment zone is confined between the well-mixed layer and the stably stratified free atmosphere aloft. It is defined in a horizontally averaged sense. This layer is a result of the interaction of turbulent eddies or thermals at the top of the mixed layer with the stratified air above. Within the entrainment zone a thermal can be considered as a core consisting mainly of air from the mixed layer surrounded by a contorted layer of air from the mixed layer and free atmosphere (Crum et al., 1987). Overshooting of thermals causes entrainment of large parcels of free air between eddies into the mixed layer. Stull (1973), Zeman and Tennekes (1977), and Mahrt (1979) used a momentum balance to calculate the thermal overshoot distance, d, as function of its initial upward velocity (assumed proportional to w_*) and the stratification of the entrainment zone:

$$d \propto \frac{w_*^2}{(g/T_0)\Delta\theta} \, . \tag{5}$$

Assuming the entrainment zone thickness is proportional to d, and using the definition of Ri^*, we find that Eq. (5) becomes Eq. (2). Clearly, the relationship (2) is a direct result of the original parcel theory. The basic assumption is that the thermal's initial upward velocity is proportional to w_*.

Using the integrated turbulent-kinetic-energy equation over the depth of the mixed layer, Gryning and Batchvarova (1994) obtained the expression for the balance between the consumption of energy by the entrainment process and the production of turbulent kinetic energy:

$$-W_*^3 = Aw_*^3 + Bu_*^3 \, , \tag{6}$$

where W_* is the top-down velocity scale (Sorbjan, 1990), u_* is the friction velocity, A and B are dimensionless parameterization constants. As can be seen from Eq. (6), the effect of both convective and mechanical turbulence is contained in W_*. Its use is, therefore, not limited to convective conditions, and implies that the original parcel theory is not perfect. But Gryning and Batchvarova (1994) still applied the parcel theory which assumed that W_*^2 is proportional to

$$\frac{g}{T_0}\frac{\Delta\theta}{\Delta h}\Delta h^2 \, .$$

By defining the entrainment Richardson number

$$Ri_{\mathrm{E}} \equiv \frac{g}{T_0}\Delta\theta h / w_e^2 \, ,$$

where w_e is the entrainment rate, they obtained a parameterization for the entrainment scheme

$$\frac{\Delta h}{h} \propto Ri_{\mathrm{E}}^{-1/3} \, .$$

The datasets of Deardorff et al. (1980) and Boers and Eloranta (1986) fit this relationship very well, and suggest that:

$$\frac{\Delta h}{h} = \frac{3.3}{Ri_{\mathrm{E}}^{1/3}} + 0.2 \, . \tag{7}$$

If Deardorff et al.'s (1980) parameterization for the entrainment rate such as

$$w_e/w_* = A \cdot Ri_i^{*-1}$$

(where A=0.25) is introduced into Equation (7), it turns out to be:

$$\frac{\Delta h}{h} = \frac{1.31}{Ri^*} + 0.2 \, . \tag{8}$$

Eq. (8) is much more similar to Eq. (4), but it does not fit well to the data of Boers and Eloranta (1986). Gryning and Bathvarova (1994) attributed this phenomenon to the use of w_* which is in the definition of the convective Richardson number Ri^*. They pointed out the fact that Boers and Eloranta's (1986) data were not gathered under purely convective conditions. In this case, shear production of turbulent kinetic energy was present and can be important for the entrainment process and structure of the entrainment zone. This indicates that w_* is not the proper scaling velocity at the top of the mixed layer. However, Gryining and Batchvarova's (1994) result does not deny the parcel theory. The relationship

$$\frac{\Delta h}{h} \propto Ri_{\mathrm{E}}^{-1/3}$$

is just obtained based on the parcel theory.

Although Ri_{E} is better than Ri^* in parameterization of the entrainment-zone depth, it does not explain how the mechanical turbulence and wind shear influence the entrainment process. Since the entrainment rate w_e which is included in Ri_{E} is usually unknown, it is difficult to apply Gryning and Batchvarova's (1994) scheme. But the result of Gryning and Batchvarova (1994) is important. It suggested that Ri^* might be an improper parameter for the parameterization of the entrainment process. It can be seen clearly that Eq. (8) is deduced from Eq. (7) by using the parameterization scheme

$$w_e/w_* = A \cdot Ri_i^{*-1} \, .$$

2.2 *Analyses on the physics of* Ri^* *and its applicability*

The convective Richardson number Ri^* is a dimensionless characteristic parameter that is always used to represent the intensity of convection in the mixed layer. Up to now, most parameterization schemes about the entrainment process are related to Ri^*. But as mentioned in the introduction, when Ri^* is used to parameterize the normalized entrainment-zone depth, there exist large differences among the results of various studies. Moreover, demonstrated as Eq. (4) or Eq. (8), when $Ri^* \to \infty$ ($w_* \to 0$), there is no convection in the boundary layer, and the two formulas turn out to be $\Delta h \sim 0.2h$. This means that the entrainment zone still maintains a certain thickness under non-convective conditions. Boers and Eloranta (1986) attributed the asymptotic value of Δh to the gravity wave riding on the interface. But it seems difficult to maintain the gravity waves without the convective forcing from the mixed layer. Another explanation is that Kelvin-Helmholz instabilities cause the asymptotic values of Eq. (4) or Eq. (8). In the presence of ambient wind shear, Kelvin-Helmholz waves might occur. Then these waves might breakdown and become turbulence, which might contribute to the entrainment at the top of the boundary layer. But it cannot explain why the depth of the entrainment zone has a fixed proportion to the boundary-layer height in the case of no convection. Unfortunately, the asymptotic value was suggested by Deardorff et al.'s (1980) experiment data measured in a water tank, where the wind shear did not exist. Investigators have not yet given a reasonable explanation on this. Beyrich and Gryning's (1998) sodar data show that no obvious relationship can be found when plotting $\Delta h/h$ against the convective Richardson number Ri^*. These suggest that using Ri^* to parameterize the entrainment process might not be suitable.

$\theta_* = \overline{(w'\theta')}_s/w_*$ is defined as the convective turbulent temperature scale. It can be regarded as the characteristic scale of the temperature difference between the parcel and the bulk of the mixed layer. Then $(g/T_0)\theta_*$ is the buoyancy forcing on the parcel in the mixed layer, and $(g/T_0)\theta_* h$ is the characteristic scaling work done by the buoyancy across the mixed layer. The characteristic kinetic energy $w_0^2/2$ of the parcel at the top of the mixed layer should be proportional to the characteristic buoyancy work. This leads to

$$\frac{1}{2}w_0^2 \propto \frac{g}{T_0}\theta_* h \, .$$

According to the parcel theory assuming that a mixed-layer parcel traveling upward into the stable air loses its kinetic energy while gaining potential energy, written as

$$\frac{1}{2}w_0^2 \propto \frac{g}{T_0}\Delta\theta\Delta h \, ,$$

it obviously leads to

$$\frac{g}{T_0}\theta_* h \propto \frac{g}{T_0}\Delta\theta\Delta h \, , \tag{9}$$

or

$$\frac{\Delta h}{h} \propto \frac{\theta_*}{\Delta\theta} \, . \tag{10}$$

From the definitions of Ri^*, w_* and θ_*, the relationship $Ri^* = \Delta\theta/\theta_*$ can be obtained, and Eq. (10) is equivalent to Eq. (2). That is to say, when assuming that the characteristic vertical velocity at the top of the mixed layer is attributed to the contribution of the thermal convective turbulence, the result of the original parcel theory must be as Eq. (2). However, there are other components such as mechanical turbulence and wind shear in the real convective boundary layer that can influence the entrainment process and the structure of the entrainment zone. That is to say, although Ri^* is defined as a characteristic parameter and can represent the strength of convection in the mixed layer to a greater or lesser extent, it cannot describe the normalized entrainment-zone depth properly.

3. New parameterization for the depth of the entrainment zone

3.1 *The influence of the lapse rate of the capping inversion layer*

From the data of Deardroff et al. (1980) and Boers and Eloranta (1986), it can be seen obviously that the entrainment-zone depth is governed by the strength of the capping inversion layer. The same result was found for the lidar-based data of MERMOZ (Hageli et al., 2000). These facts indicate that the lapse rate Γ of the capping inversion layer plays an important role in the entrainment process. Therefore, it should be taken into account in the parameterization scheme.

Both Deardorff et al.'s (1980) data and Boers and Eloranta's (1986) data show that $\Delta\theta$ and Γ are independent. But the compound $\Delta\theta/\Delta h$ has a good correlation with Γ. This relationship is also supported by the result of the ROSE II experiment (Angevine et al., 1994). From Fig. 2 it can be seen that the positive correlation between $\Delta\theta/\Delta h$ and Γ is obvious. The data of Deardorff et al. (1980) order the linear correlation nicely when the data with $\Gamma < 10°\mathrm{C\ m^{-1}}$ and $\Gamma > 400°\mathrm{C\ m^{-1}}$ are removed. The correlation coefficient is 0.88 (see Fig. 2a). This leads to a new problem of determining under what conditions the convective mixed layer modeled in a water tank will be close to that in the real atmosphere. This problem goes beyond the context discussed in this paper. The data of Boers and Eloranta (1986) do not order a linear correlation perfectly. The fit situation is remarkably improved and the linear correlation becomes acceptable when the data with clouds present are excluded (see Fig. 2b). Because under these weather conditions the entrainment process may include the potential heat exchange, this situation is not considered in this paper.

The data of Deardorff et al. (1980) and Boers and Eloranta (1986) show that the relationship between $\Delta\theta/\Delta h$ and Γ can be written as:

$$\frac{\Delta\theta}{\Delta h} = B\cdot\Gamma \, . \tag{11}$$

Here, B is constant. Equation (11) is obviously a phenomenological result. It is not clear what factors cause the linear correlation between $\Delta\theta/\Delta h$ and Γ. Evidence shows that this result reflects certain aspects of the entrainment process. If this relationship could be deduced theoretically by using a proper physical model, it would help to completely understand the entrainment process, even to reveal the mechanism of entrainment.

3.2 *New parameterization*

Based on the fact that the lapse rate Γ of the capping inversion layer plays an important role in the en-

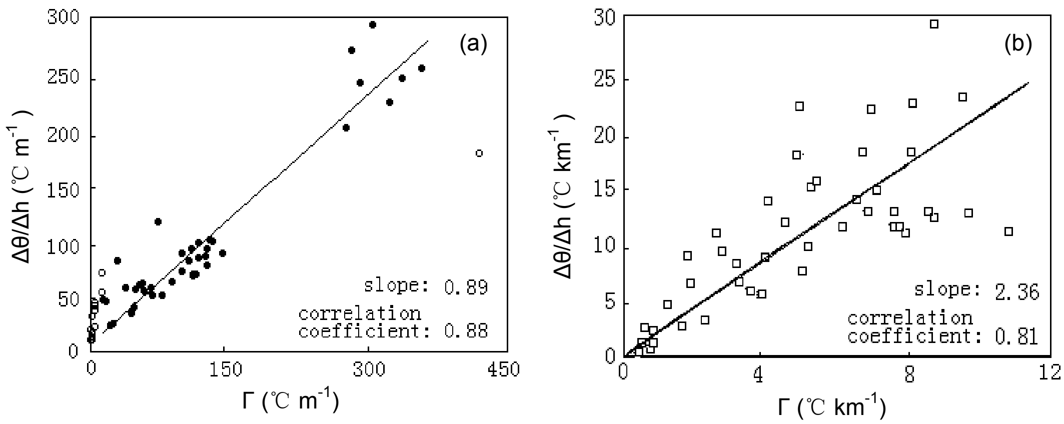

Fig. 2. Correlations between $\Delta\theta/\Delta h$ and Γ : (a) Date of Deardorff et al.'s (1980) water-tank experiments, $\bullet$ Data with $10^{\circ}\mathrm{C\,m^{-1}}$, $\circ$ Data with $\Gamma \leqslant 10^{\circ}\mathrm{C\,m^{-1}}$ and $\Gamma \geqslant 400^{\circ}\mathrm{C\,m^{-1}}$, (b) Data of Boers and Eloranta's (1986) atmospheric measurements in CIRCE.

trainment process, we induct Γ into our new parameterization scheme for the depth of the entrainment zone.

Still based on the parcel theory, rewrite Eq. (1) as follows:

$$\Delta h = C' w_*^2 / \left(\frac{g}{T_0}\Delta\theta\right) . \tag{12}$$

Here C' is a constant. From Eq. (11), the potential temperature jump $\Delta\theta = B \cdot \Gamma\Delta h$ can be obtained. Then the above equation becomes

$$\Delta h = C'' w_*^2 / \left(\frac{g}{T_0}\Gamma\Delta h\right) , \tag{13}$$

or

$$\left(\frac{\Delta h}{h}\right)^2 = C'' w_*^2 / \left(\frac{g}{T_0}\Gamma h^2\right) . \tag{14}$$

Here C'' is a constant. By using the definitions of w_* and θ_*, it is easy to obtain that

$$w_*^2 = \frac{g}{T_0}\theta_* h .$$

Inserting this relationship into Equation (14) gives

$$\left(\frac{\Delta h}{h}\right)^2 = C''\frac{\theta_*}{\Gamma h} , \tag{15}$$

or

$$\frac{\Delta h}{h} = C \cdot \left(\frac{\theta_*}{\Gamma \cdot h}\right)^{1/2} = C \cdot S^{1/2} . \tag{16}$$

Here, C is constant and S is a dimensionless number.

Equation (16) shows that the normalized depth of the entrainment zone depends on the dimensionless number S to the 1/2 power. When the lapse rate 1/2 power. When the lapse rate Γ of the capping inversion layer is large, the entrainment process is depressed and $\Delta h/h$ is small. Meanwhile, the effect of the convection strength in the mixed layer is represented by θ_* which corresponds to the buoyancy in the mixed layer. When θ_* is large, the buoyancy forcing on the parcel is large. So the convection is strong and consequently $\Delta h/h$ is large. The physics of this relationship is reasonable.

Nelson et al. (1989) analyzed the data measured during BLX83 (Boundary Layer Experiment-1983), which was performed in the plains near Chickasha, Oklahoma (Stull and Eloranta, 1984). When the normalized entrainment-zone depth $\Delta h/h$ was plotted as a function of the normalized entrainment rate, w_e/w_*, with time as a parameter, a hysteresis behavior was observed. They used a thermodynamic model to simulate the hysteresis behavior. The result showed that the hysteresis curve was sensitive to the shape of the initial temperature profile in the morning and to the evolution of surface heat flux. This implies that the entrainment-zone depth is significantly influenced by the lapse rate Γ of the capping inversion layer and the turbulent temperature scale, θ_*. Based on MERMOZ II data, Hageli et al. (2000) pointed out that the location and the thickness of the entrainment zone is governed by the magnitude of the surface sensible heat flux and the strength of the capping inversion. These indicate that Γ and θ_* are proper to characterize the entrainment-zone depth.

In view of parcel theory, the meaning of Eq. (16) is very clear. It was mentioned in the last section that $(g/T_0)\theta_* h$ should be proportional to the parcel's kinetic energy $w_0^2/2$ at the top of the mixed layer. When overshooting into the capping inversion layer, the parcel loses it kinetic energy and gains potential energy. The energy balance leads to

$$\frac{1}{2}w_0^2 \propto \frac{g}{T_0}\frac{\Delta\theta}{\Delta h} \cdot \Delta h^2 .$$

It is easy to obtain that

$$\frac{g}{T_0}\theta_* h \propto \frac{g}{T_0}\frac{\Delta\theta}{\Delta h}\cdot \Delta h^2 \ . \tag{17}$$

Using Eq. (11), one can obtain that

$$\theta_* h \propto \Gamma \cdot \Delta h^2 \ , \tag{18}$$

which can be written as follows:

$$\Delta h = C \cdot \left(\frac{\theta_* h}{\Gamma}\right)^{1/2} \ . \tag{19}$$

This equation is the same as Eq. (16). Although Eq. (16) cannot include the effects of mechanical turbulence and wind shear, its physics is clear and reasonable. In our opinion, parameterization should emphasize the physical process. Actually, most parameterizations are based on simplified physical models, but they should still describe clear physical processes. The convective Richardson number Ri^* is based on empirical thinking and it cannot describe a clear physical process. Maybe this leads to its failure in parameterizing of the entrainment process.

3.3 *Data comparison*

Figure 3 gives the correlations between the normalized entrainment-zone depth $\Delta h/h$ and the dimensionless number S according to the two datasets of Deardorff et al. (1980) and Boers and Eloranta (1986). It can be seen that when the normalized entrainment-zone $\Delta h/h$ is plotted as a function of $S^{1/2}$, the data of Boers and Eloranta (1986) follows a linear relationship very nicely, where the lapse rate Γ in the capping inversion layer is computed by using $\Delta\theta, \Delta\theta_2, h_0, h$ and Δh (Boers and Eloranta, 1986). When the data are

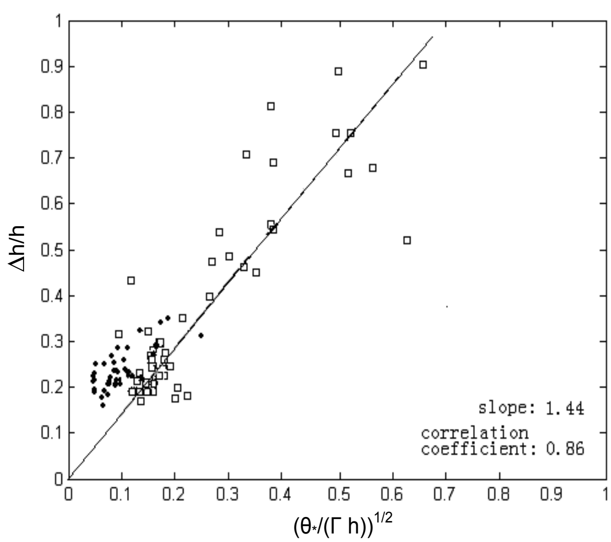

Fig. 3. Correlation between $\Delta\theta/\Delta h$ and $[\theta_*/(\Gamma h)]^{1/2}$. • Boers and Eloranta's (1980) data. □ Deardorff et al's (1980) data with $10°\text{C m}^{-1} < \Gamma < 400°\text{C m}^{-1}$. – fit of Boers and Elorant's data.

fitted using Eq. (16), a best fit value of the constant C is 1.44. The data of Deardorff et al. (1980) show a similar situation to relationship (11). When the data with Γ <10°C m^{-1} and Γ >400°C m^{-1} are removed, the order is improved, and the fit value of the constant C is 2.37. According to the dimensionless number S, the extent of convection in the mixed layer modeled in Deardorff et al.'s (1980) water tank varies over a narrow range. The normalized entrainment-zone depth does not change largely and is around a typical value of 0.2–0.3. Although the tendency is not very clear, the linear relationship is still acceptable. Both datasets show that the normalized depth $\Delta h/h$ depends on the dimensionless number S to the 1/2 power. This indicates that the parcel theory is not invalid.

The difference of constant C between the two datasets implies that the convective boundary-layer simulated in the water tank is different from that in the real atmosphere. This difference is very interesting. As show in Fig. 3, when the dimensionless number is small (S<0.2), the normalized depth $\Delta h/h$ in Deardorff et al.'s (1980) data is systematically larger than that in Boers and Eloranta's (1986) data. Similarly, according to the parameterization scheme of Gryning and Batchvarova (1994) expressed as $\Delta h/h \propto Ri_{\rm E}^{-1/3}$, the normalized depth $\Delta h/h$ in Deardorff et al.'s (1980) data is also obviously larger than that in Boers and Eloranta (1986)'s data when Ri_E is around 10^4 (Gryning and Batchvarova, 1994). This phenomenon cannot be explained directly by turbulent energy. Because the turbulent energy in the real mixed layer includes not only thermal turbulence but also the contribution of mechanical turbulence and wind shear, the total turbulence should be stronger. Why does the normalized depth become smaller? It seems that wind shear is an important factor which can influence the parcel's behavior when it is overshooting in the stable air. Up to now, it is not clear whether the effect of wind shear would be to increase or decrease the depth of the entrainment zone.

4. Conclusions and discussion

The traditional method using the convective Richardson number Ri^* to parameterize the entrainment process seems to be improper. Based on the assumption that the normalized depth of the entrainment zone is a function of Ri^*, investigators concluded various parameterization schemes. It has not been possible to establish one general parameterization for the entrainment-zone depth. Most of them attribute this situation to parcel theory and believe that parcel theory is invalid. Evidence shows that the reason is not parcel theory but the Richardson number Ri^* itself. Because Ri^* does not have a clear physical meaning and cannot be connected with a clear physical process, its value may not be consistent with the extent of entrainment. These indicate that the convective Richardson number Ri^* is not a proper parameter to characterize the entrainment process. More suitable parameterization schemes should be investigated.

The lapse rate Γ of the capping inversion layer is an important factor which can influence the entrainment process. But the conventional schemes using Ri^* do not include the effect of Γ. The fact that Γ plays an important role in the entrainment process suggests that it should be taken into account in the parameterization schemes. Deardorff et al.'s (1980) experiment data and Boers and Eloranta's (1986) lidar data have been analyzed in this paper. It is found that the total lapse rate $\Delta h/h$ of the entrainment zone is proportional to the lapse rate Γ of the capping inversion layer. This relationship can conveniently help introduce Γ into the parameterization scheme for the entrainment. Why this relationship can be established in the real atmosphere is an interesting problem and should be studied further.

A new parameterization for the depth of the entrainment zone, written as Eq. (16), is obtained by using relationship (11) and parcel theory. This new scheme describes a clear physical process and the result is reasonable. It gives a nice ordering of the data of two earlier studies by Deardorff et al. (1980) and Boers and Eloranta (1986). This indicates that parcel theory can represent the main character of the convective boundary layer. There is no doubt that parcel theory is valid under fully convective conditions. However, the new parameterization does not include the effects of mechanical turbulence and wind shear. But the agreement between Eq. (16) and the data of Boers and Eloranta (1986), which were not selected under purely convective conditions, suggests that parcel theory can also be suitable when mechanical turbulence and wind shear exist in the real atmosphere. This does not imply that the mechanical turbulence and wind shear are not important. It should be investigated in the future how a parcel interacts with mechanical turbulence or wind shear.

Another interesting phenomenon is that under the same thermal convective conditions, the normalized depth $\Delta h/h$ in the real atmosphere is systematically smaller than in a water tank. It is believed that the mechanical turbulence at the top of the mixed layer is very weak and can be neglected as compared with the convective turbulence. Our water-tank experiments show that the turbulent velocity at the top of the mixed layer is mainly vertical (Li et al., 2003). These imply that the wind shear may be an important factor which can influence a parcel's behavior in the entrainment zone. The data show that the wind shear might restrain the overshooting of the parcel. This situation seems to be similar to the elevated smoke that is controlled by the wind speed. But the newest numerical result of large eddy simulation suggests that strong wind shear can enlarge the entrainment-zone depth (Kim et al., 2003). This problem should be studied further.

Acknowledgments. This paper was supported by the National Natural Science Foundation of China under Grant Nos. 40105002 and 40333027.

REFERENCES

Angevine, W. M., A. B. White, and S. K. Avery, 1994: Boundary-layer depth and entrainment zone characterization with a boundary-layer profiler. *Bound.-Layer Meteor.*, **68**, 375–385.

Betts, A. K., 1976: Modeling subcloud layer structure and interaction with a shallow cumulus layer. *J. Atmos. Sci.*, **33**, 2326–2382.

Beyrich, F., and S. E. Gryning, 1998: Estimation of the entrainment zone depth in a shallow convective boundary layer from sodar data. *J. Appl. Meteor.*, **37**, 255–268.

Boers, R. A., 1989: A parameterization of the depth of the entrainment zone. *J. Appl. Meteor.*, **28**, 107–111.

Boers, R. A., and E. W. Eloranta, 1986: Lidar measurements of the atmospheric entrainment zone and the potential temperature jump across the top of the mixed layer. *Bound.-Layer Meteor.*, **34**, 357–375.

Crum, T. D., R. B. Stull, and E. W. Eloranta, 1987: Coincident lidar and aircraft observations of entrainment into thermals and mixed layer. *J. Climate Appl. Meteor.*, **26**, 774–788.

Deardorff, J. W., 1979: Prediction of convective mixed layer entrainment for realistic capping inversion structure. *J. Atmos. Sci.*, **27**, 1211–1213.

Deardorff, J. W., 1983: A multilimit mixed layer entrainment formulation. *J. Phys. Oceanogr.*, **13**, 988–1002.

Deardorff, J. W., G. E. Willis, and B. H. Stockton, 1980: Laboratory studies of the entrainment zone of a convectively mixed layer. *J. Fluid Mech.*, **100**, 41–64.

Gryning, S. E., and E. Batchvarova, 1994: Parameterization of the depth of the entrainment zone above the daytime mixed layer. *Quart. J. Roy. Meteor. Soc.*, **120**, 47–58.

Hageli, P., D. G. Steyn, and K. B. Strawbridge, 1993: Spatial and temporal variability of mixed-layer depth and entrainment zone thickness. *Bound.-Layer Meteor.*, **97**, 47–71.

Kim, S. W., S. U. Park, and C. H. Moeng, 2003: Entrainment process in the convective boundary layer with varying wind shear. *Bound.-Layer Meteor.*, **108**, 221–245.

Li Pingyang, Jiang Weimei, Sun Jianning, and Yuan Renmin, 2003: A laboratory modeling of the velocity field in the convective boundary with the particle image velocimetry technique. *Adv. Atmos. Sci.*, **20**(4), 631–637.

Mahrt, L., 1979: Penetrative convection at the top of a growing boundary layer. *Quart. J. Roy. Meteor, Soc.*, **105**, 469–485.

Nelson, E., R. B. Stull, and E. W. Eloranta, 1989: A prognostic relationship for entrainment zone thickness. *J. Appl. Meteor.*, **28**, 885–902.

Sorbjan, Z., 1990: Similarity scales and universal profiles of statistical moments in the convective boundary layer. *J. Appl. Meteor.*, **29**, 762–775.

Stull, R. B., 1973: Inversion rise model based on penetrative convection. *J. Atmos. Sci.*, **30**, 1092–1099.

Stull, R. B., and E. W. Eloranta, 1984: Boundary layer experiment 1983. *Bull. Amer. Meteor. Soc.*, **65**, 450–456.

Zeman, O., and H. Tennedes, 1977: Parameterization of the turbulent energy budget at the top of the daytime atmospheric boundary layer. *J. Atmos. Sci.*, **34**, 111–123.