"A Theory for Strong Long-Lived Squall Lines" Revisited

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ABSTRACT

Based on the analysis of idealized two- and three-dimensional cloud model simulations, Rotunno et al. (hereafter RKW) and Weisman et al. (hereafter WKR) put forth a theory that squall-line strength and longevity was most sensitive to the strength of the component of low-level (0–3 km AGL) ambient vertical wind shear perpendicular to squall-line orientation. An ''optimal'' state was proposed by RKW, based on the relative strength of the circulation associated with the storm-generated cold pool and the circulation associated with the ambient shear, whereby the deepest leading edge lifting and most effective convective retriggering occurred when these circulations were in near balance. Since this work, subsequent studies have brought into question the basic validity of the proposed optimal state, based on concerns as to the appropriate distribution of shear relative to the cold pool for optimal lifting, as well as the relevance of such concepts to fully complex squall lines, especially considering the potential role of deeper-layer shears in promoting system strength and longevity. In the following, the basic interpretations of the RKW theory are reconfirmed and clarified through both the analysis of a simplified two-dimensional vorticity–streamfunction model that allows for a more direct interpretation of the role of the shear in controlling the circulation around the cold pool, and through an analysis of an extensive set of 3D squall-line simulations, run at higher resolution and covering a larger range of environmental shear conditions than presented by WKR.

- The fundamental issue addressed by RKW, WKR, and the present study is why environmental vertical wind shear promotes stronger, more long-lived squall lines.
- RKW specifically addresses and explains why such low-level shear is especially beneficial, but does not purport to explain every aspect of squall-line behavior.

- System-generated features, such as rear-inflow jets or line-end vortices are certainly important components of squall-line structure, but they find that even these features develop as a consequence of the simple cold-pool–shear relationships, which they find represent the most fundamental internal control on squall-line structure and evolution.

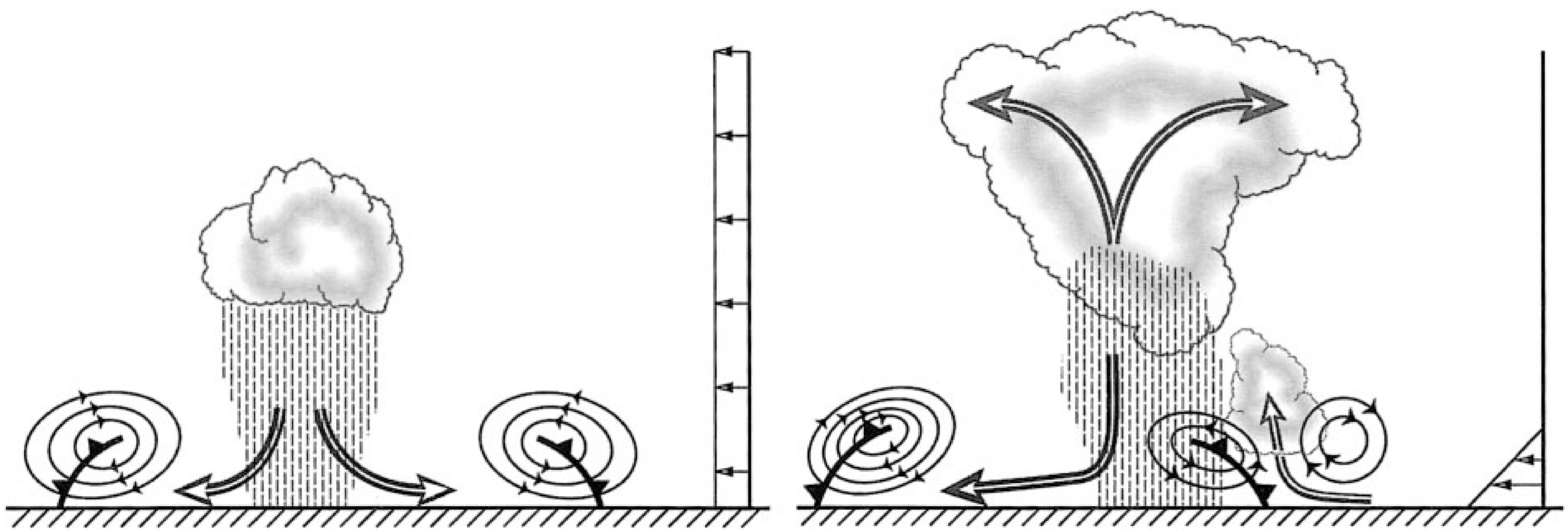
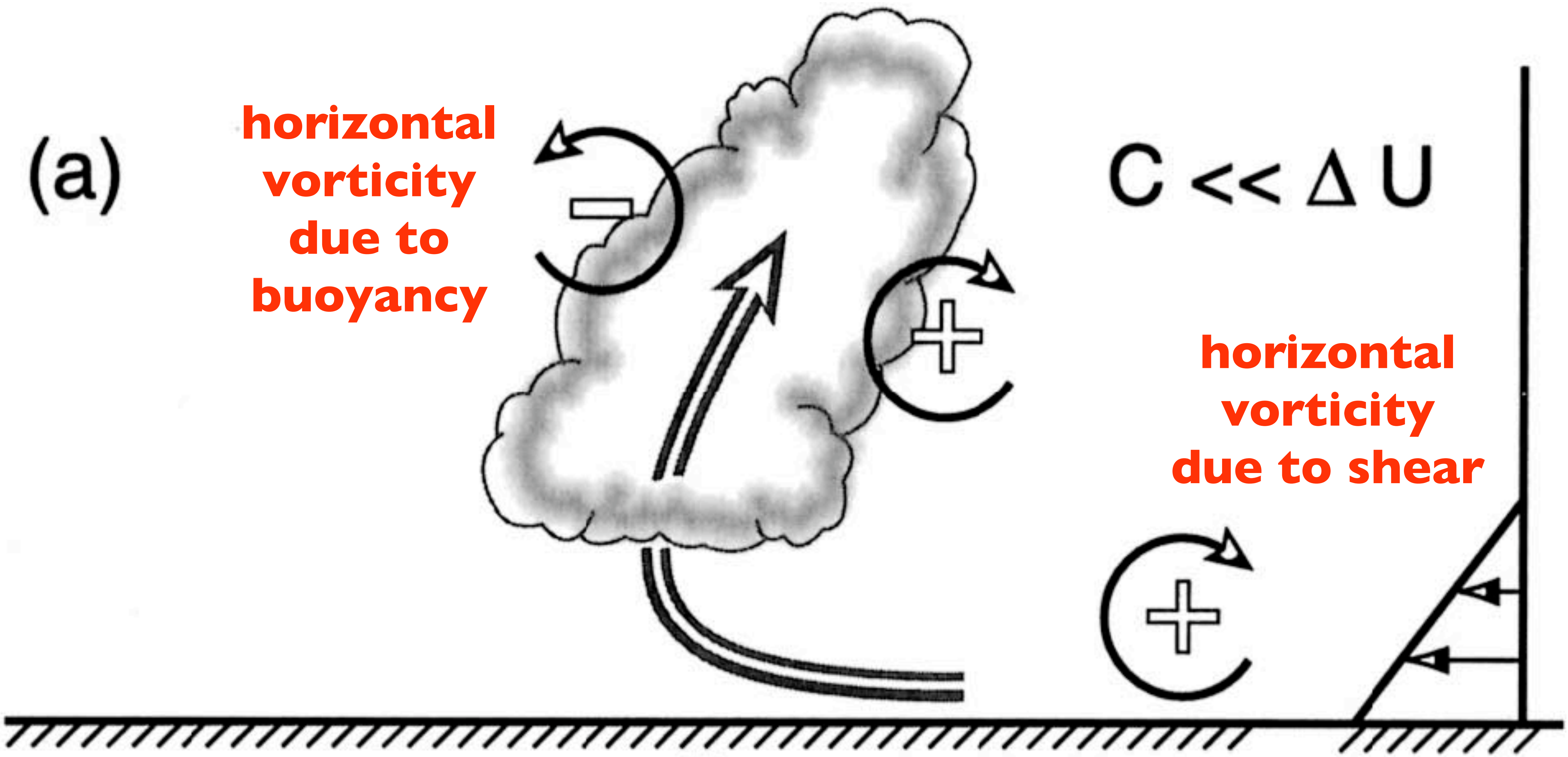


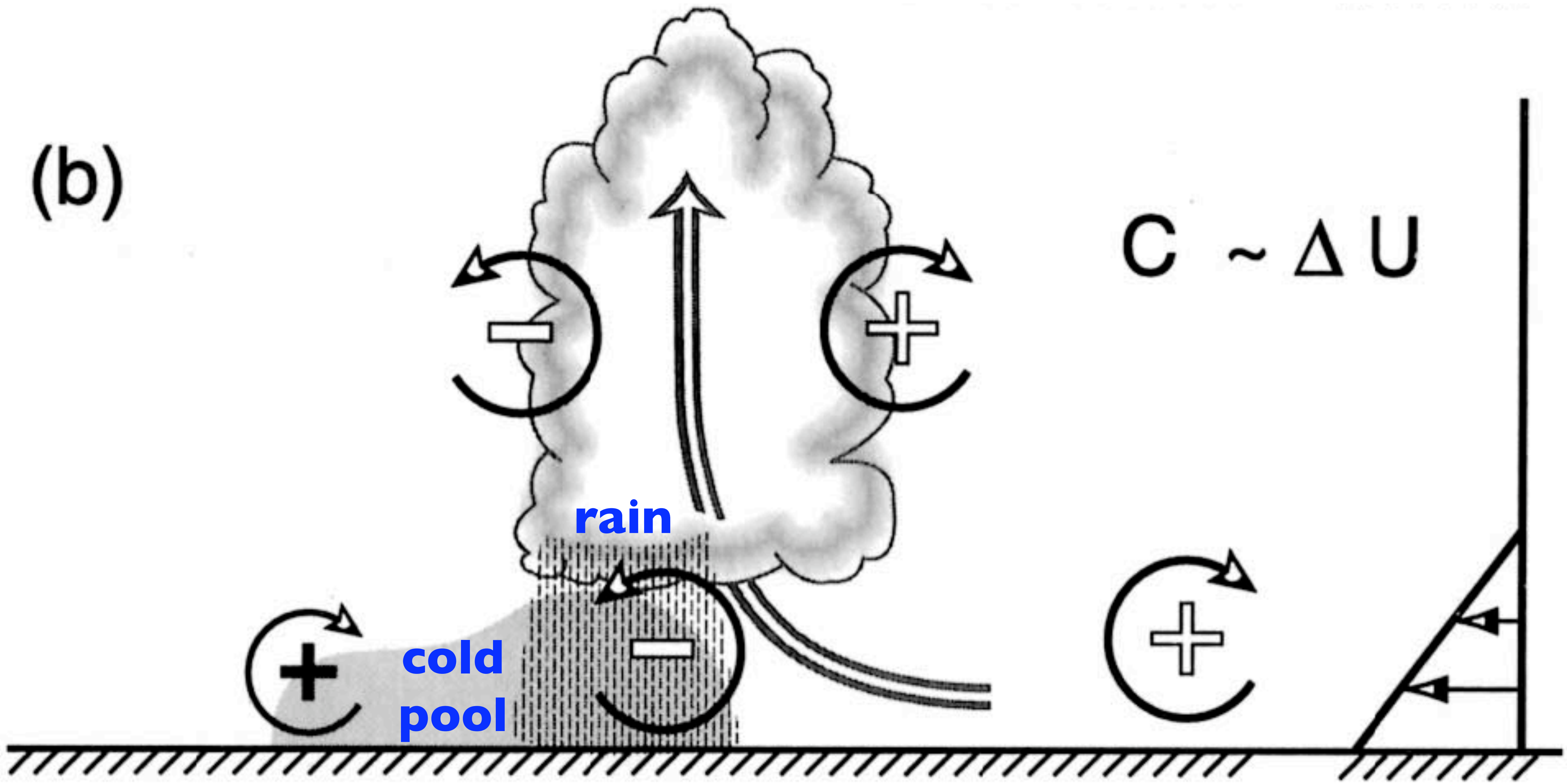
FIG. 1. (left) Cold pool spreads away from a decaying convective cell in an environment with no vertical wind shear. (right) Low-level vertical wind shear balances cold-pool circulation on the downshear side, enhancing the ability to regenerate convective cells through deeper lifting.

An initial updraft leans downshear in response to the ambient vertical wind shear, which is shown on the right.

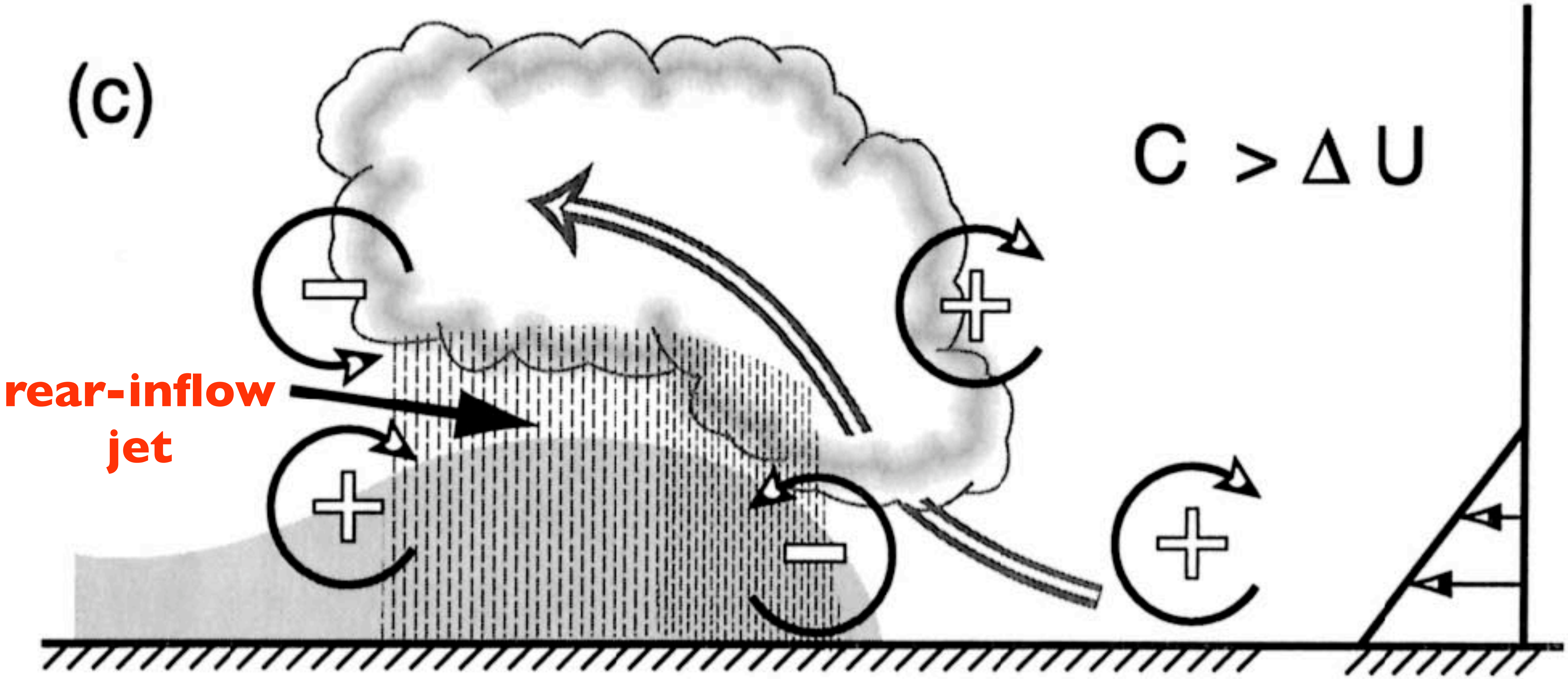
C is a velocity representing cold pool strength.
ΔU is the ambient low-level vertical wind shear.

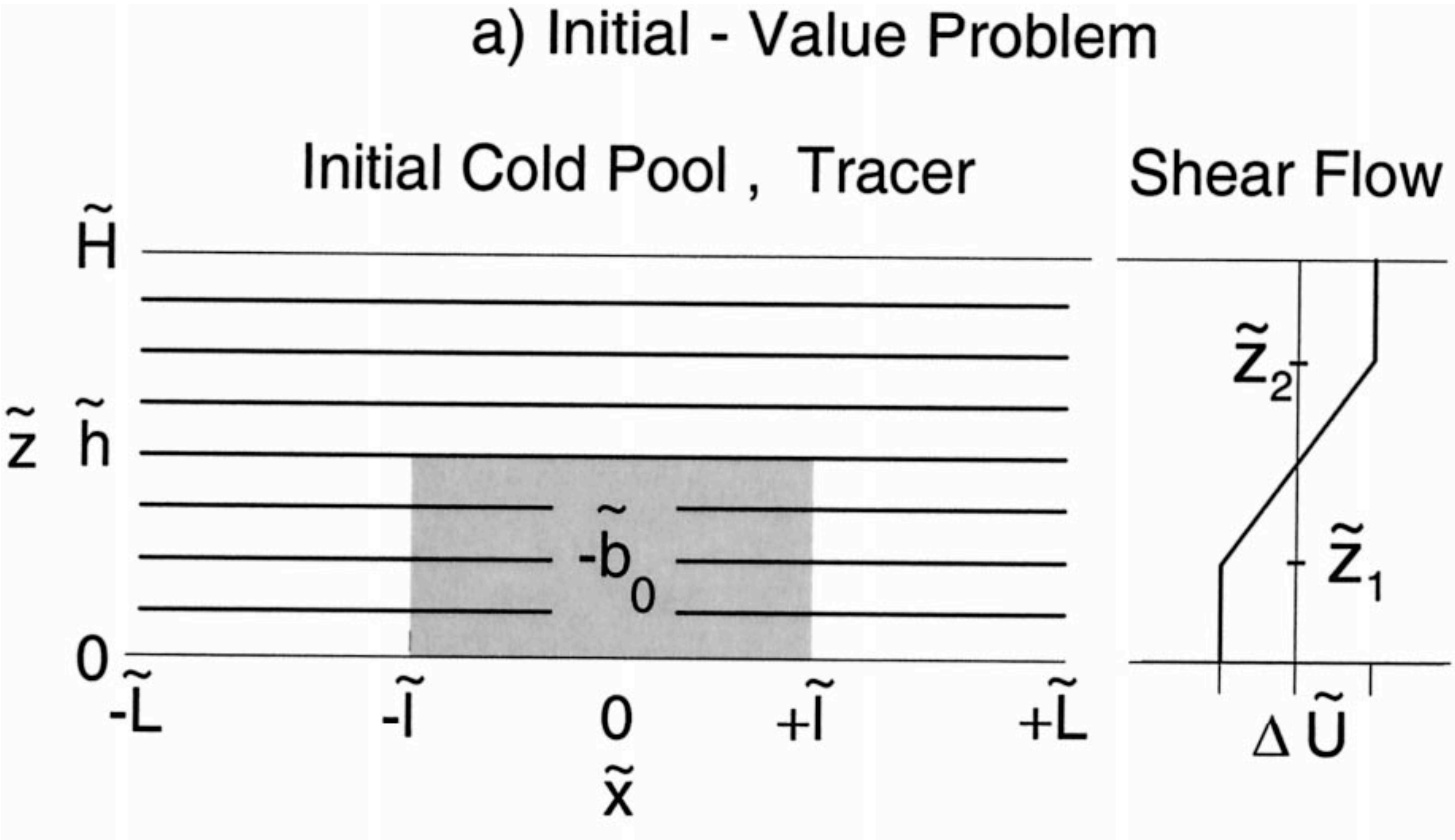


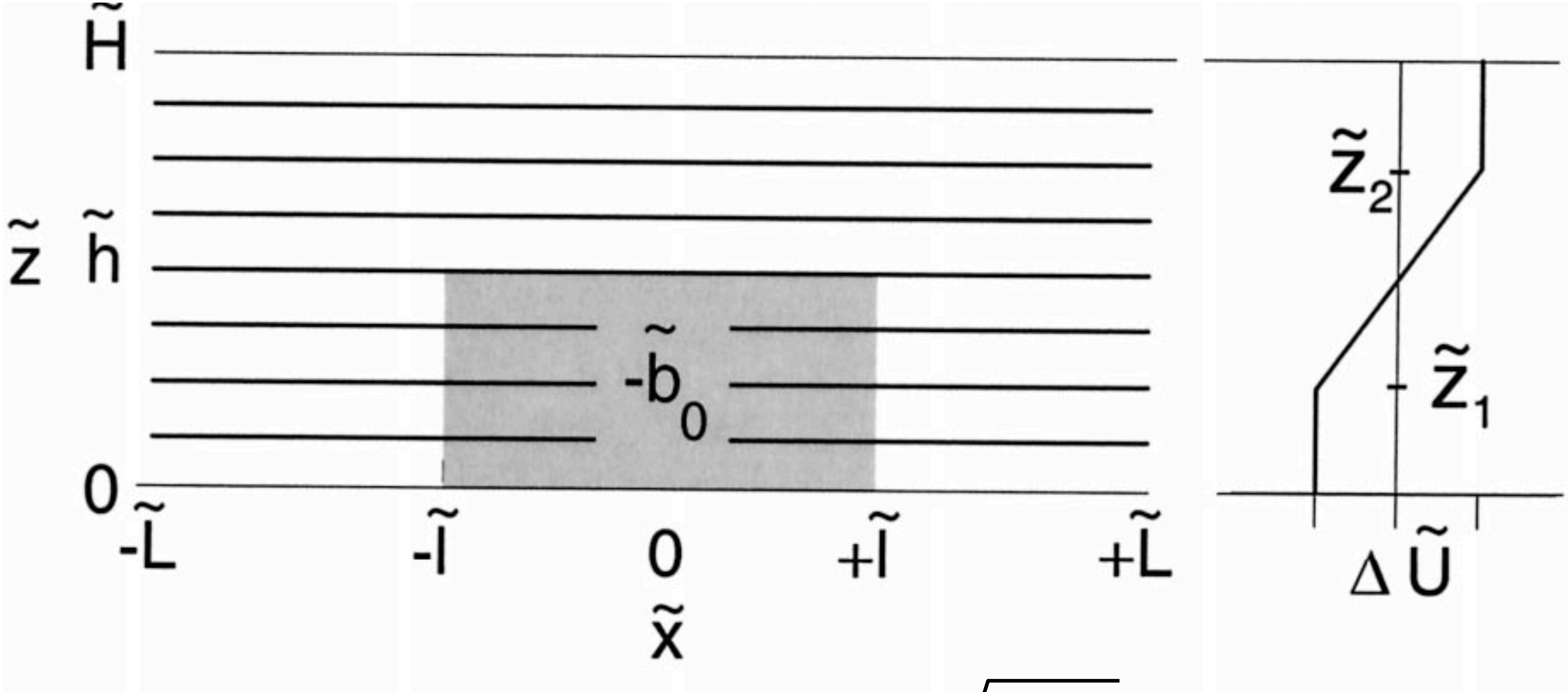
The circulation generated by the storm-induced cold pool balances the ambient shear, and the system becomes upright.



The cold-pool circulation overwhelms the ambient shear and the system tilts upshear, producing a rear-inflow jet.




a) Initial - Value Problem
Initial Cold Pool , Tracer
Shear Flow
$\tilde{H}$
$\tilde{z}$
$\tilde{h}$
0
$-\tilde{b}_0$
$\tilde{z}_2$
$\tilde{z}_1$
$-\tilde{L}$
$-\tilde{l}$
0
$+\tilde{l}$
$+\tilde{L}$
$\tilde{x}$
$\Delta \tilde{U}$

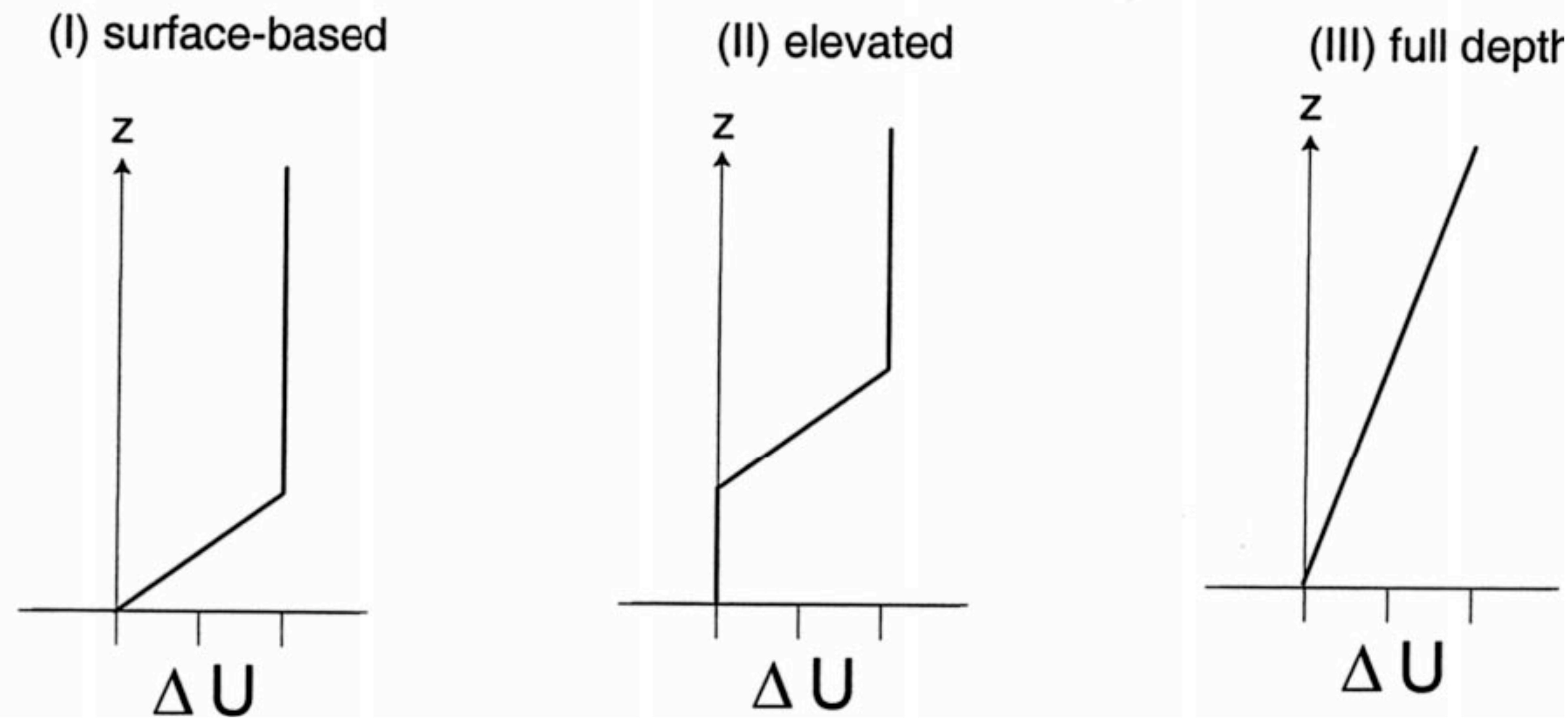


$$\Delta U = \Delta \tilde{U} / \sqrt{\tilde{b}_0 \tilde{h}}.$$

$$\Delta z = (\tilde{z}_2 - \tilde{z}_1)/\tilde{h}.$$

$$z_m = (\tilde{z}_2 + \tilde{z}_1)/2.$$

b) Shear Profiles



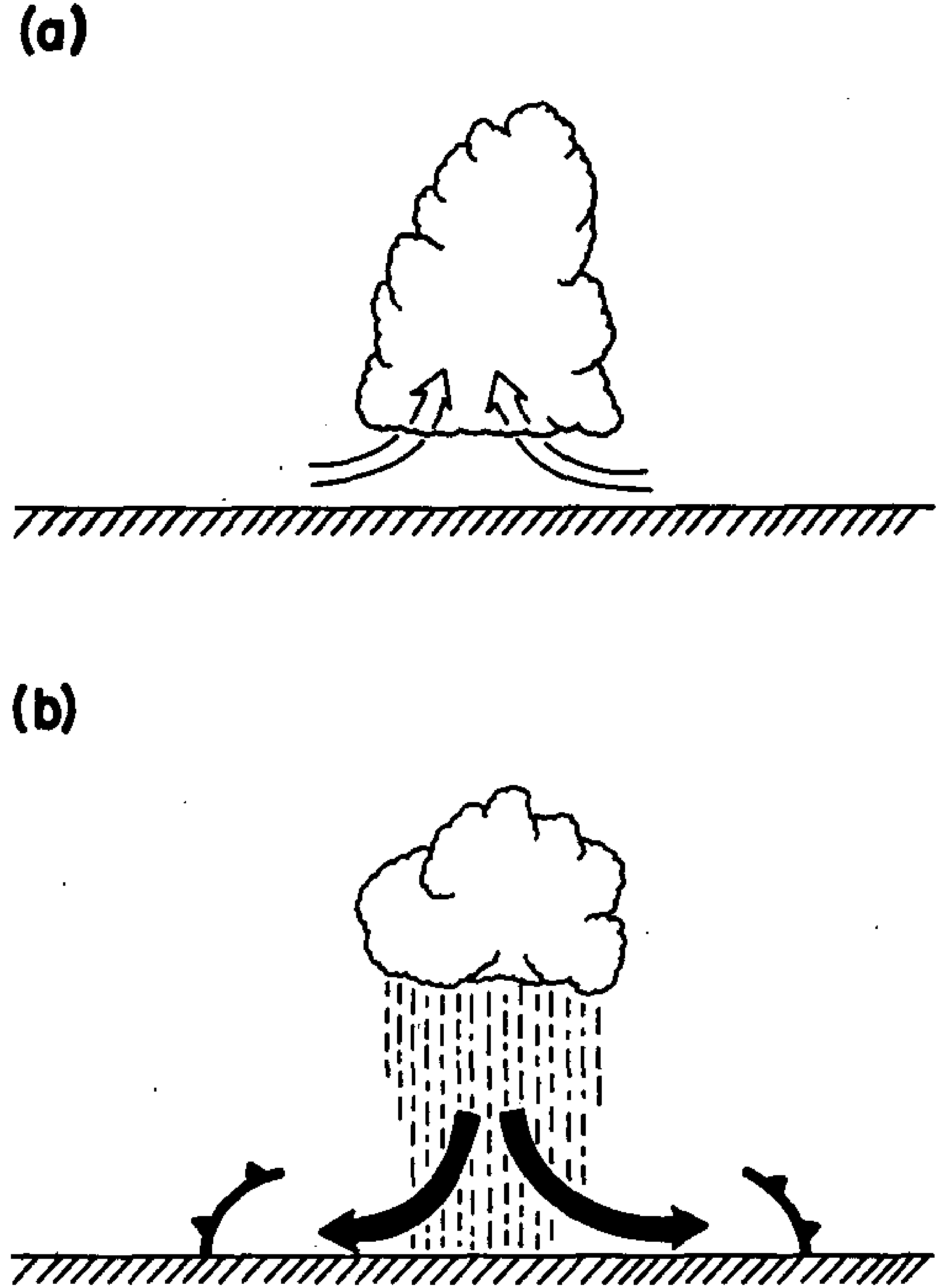
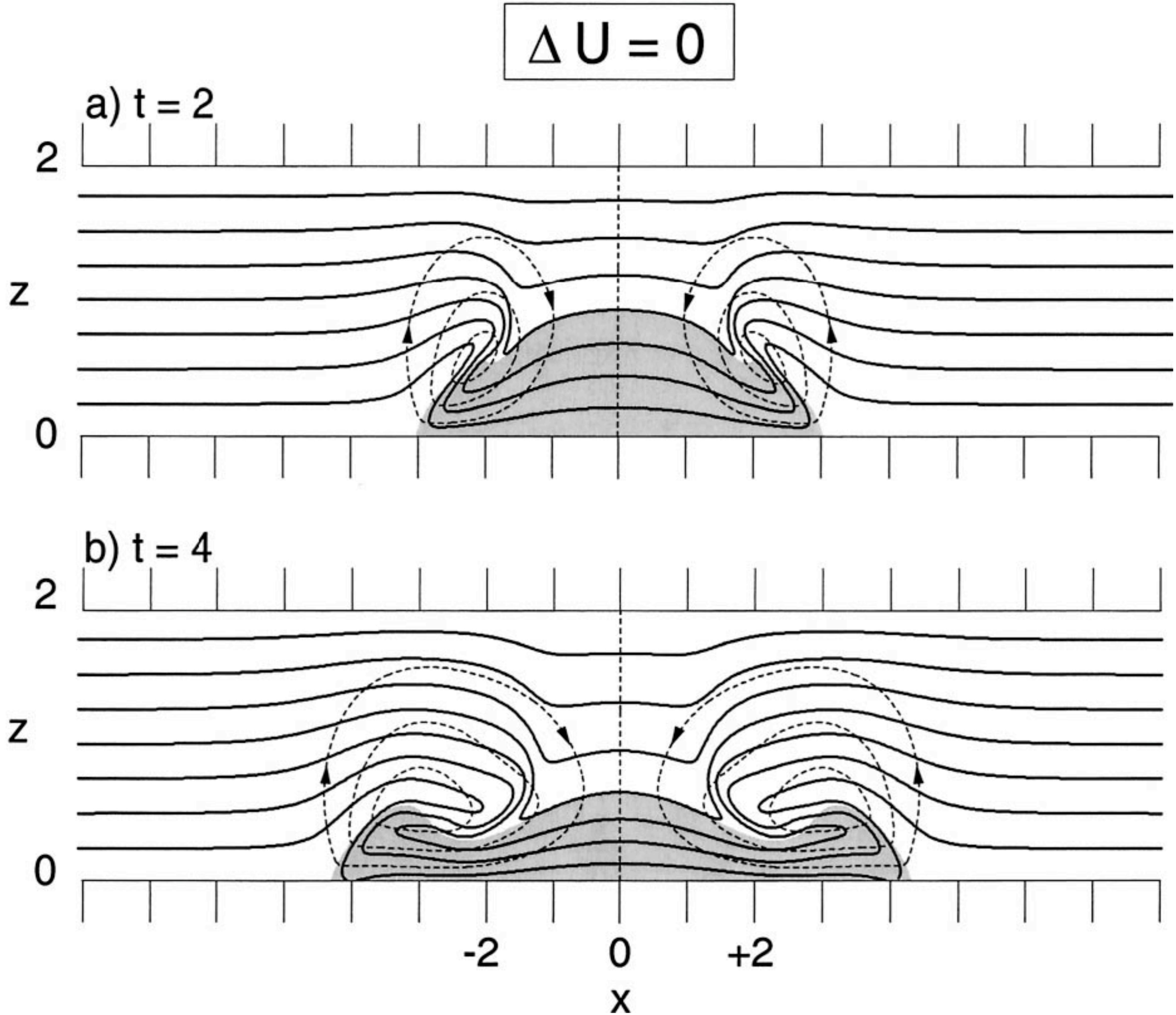
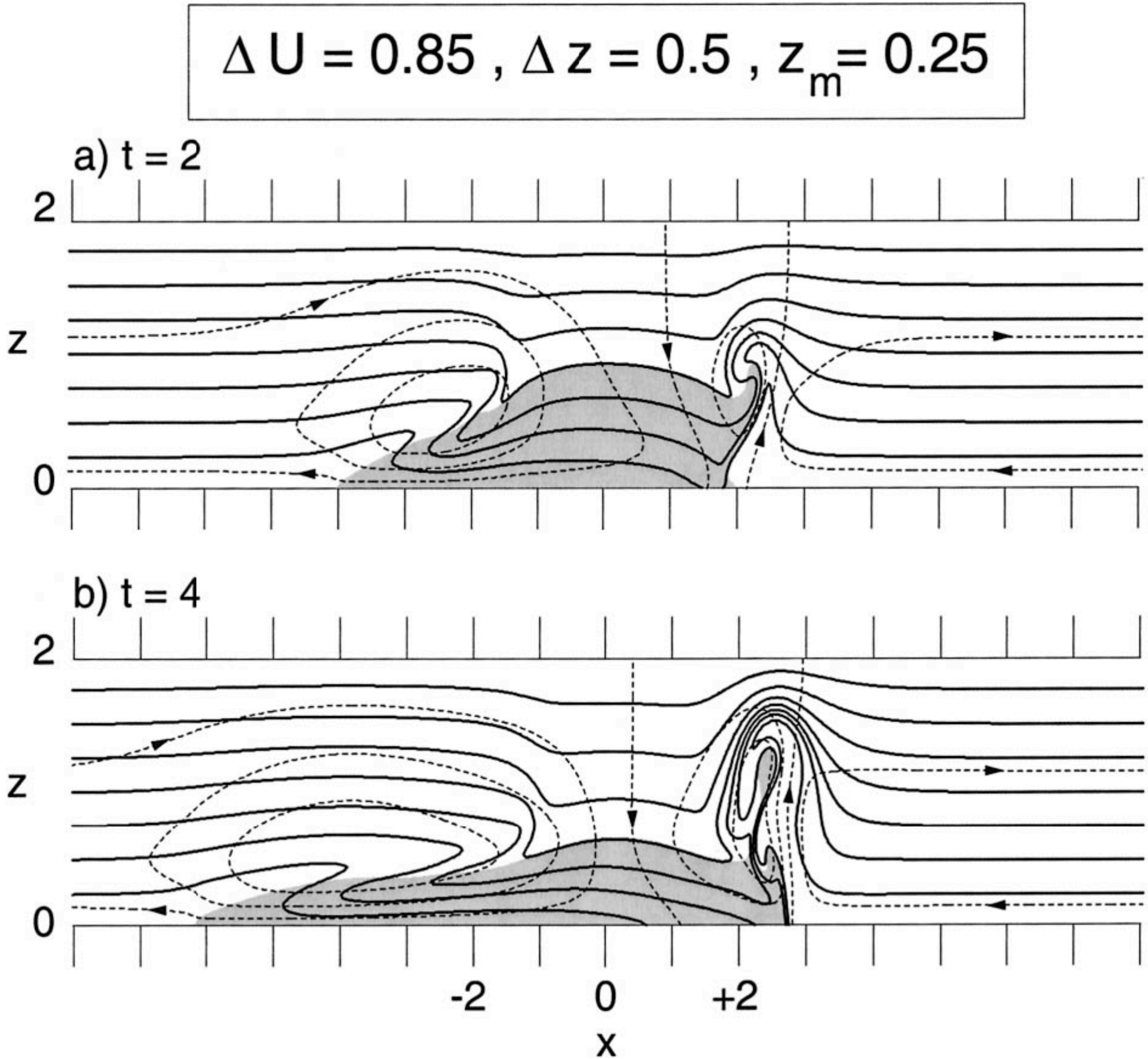


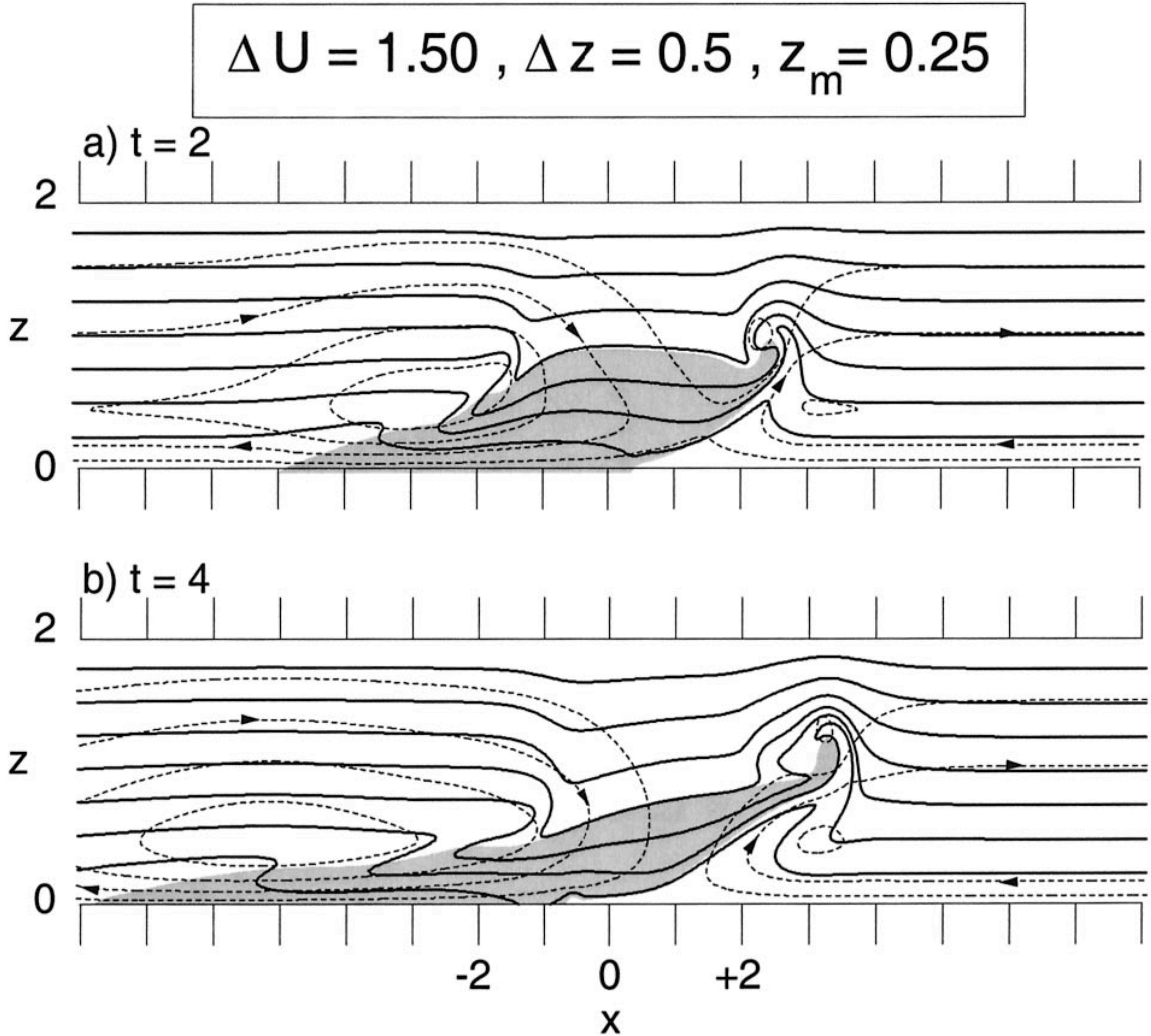
FIG. 1. Schematic illustration of the life cycle of an ordinary thunderstorm cell in which the (a) initial updraft, yields to a (b) downdraft produced by the accumulation of rain within the updraft. (Adapted from Figs. 17–18 of Byers and Braham, 1949.)



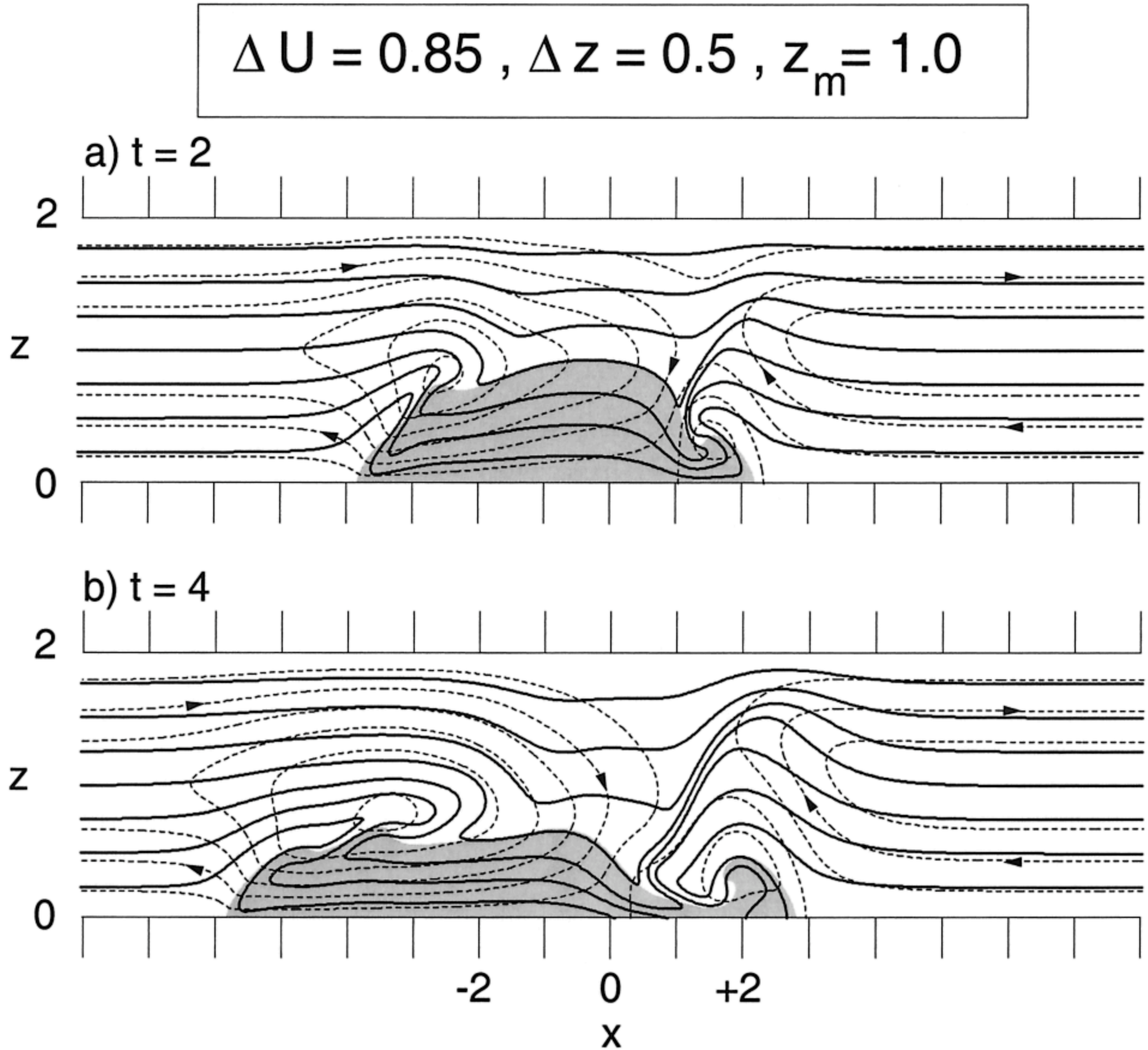
ΔU = 0
a) t = 2
2
z
0
b) t = 4
2
z
0
-2
0
+2
x



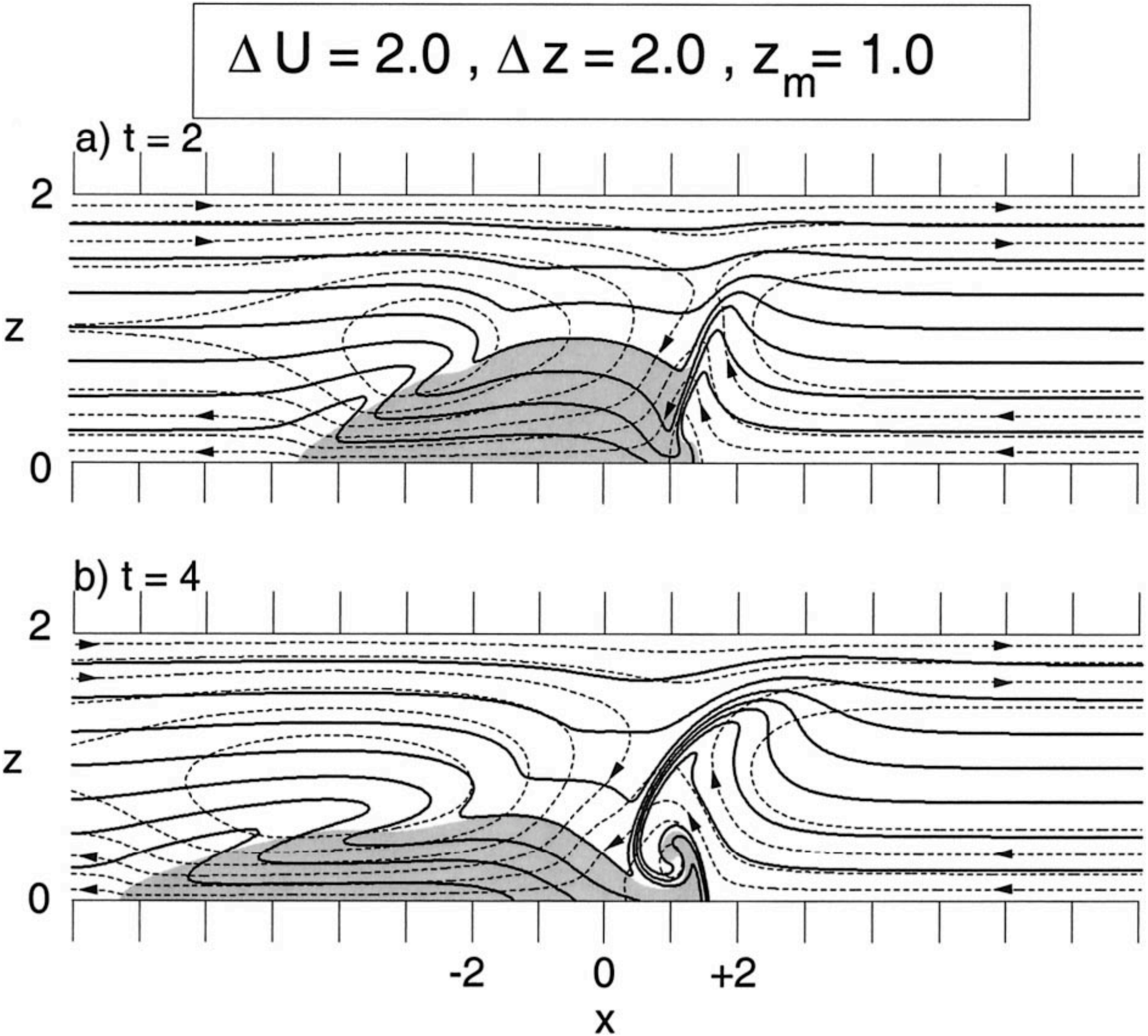
ΔU = 0.85 , Δz = 0.5 , z_m = 0.25
a) t = 2
2
z
0
b) t = 4
2
z
0
-2
0
+2
x



$\Delta U = 1.50$, $\Delta z = 0.5$, $z_m = 0.25$
a) t = 2
b) t = 4
2
0
z
-2
0
+2
x



ΔU = 0.85 , Δz = 0.5 , z_m = 1.0
a) t = 2
b) t = 4
2
0
z
-2
0
+2
x



ΔU = 2.0 , Δz = 2.0 , z_m = 1.0
a) t = 2
2
z
0
b) t = 4
2
z
0
-2
0
+2
x

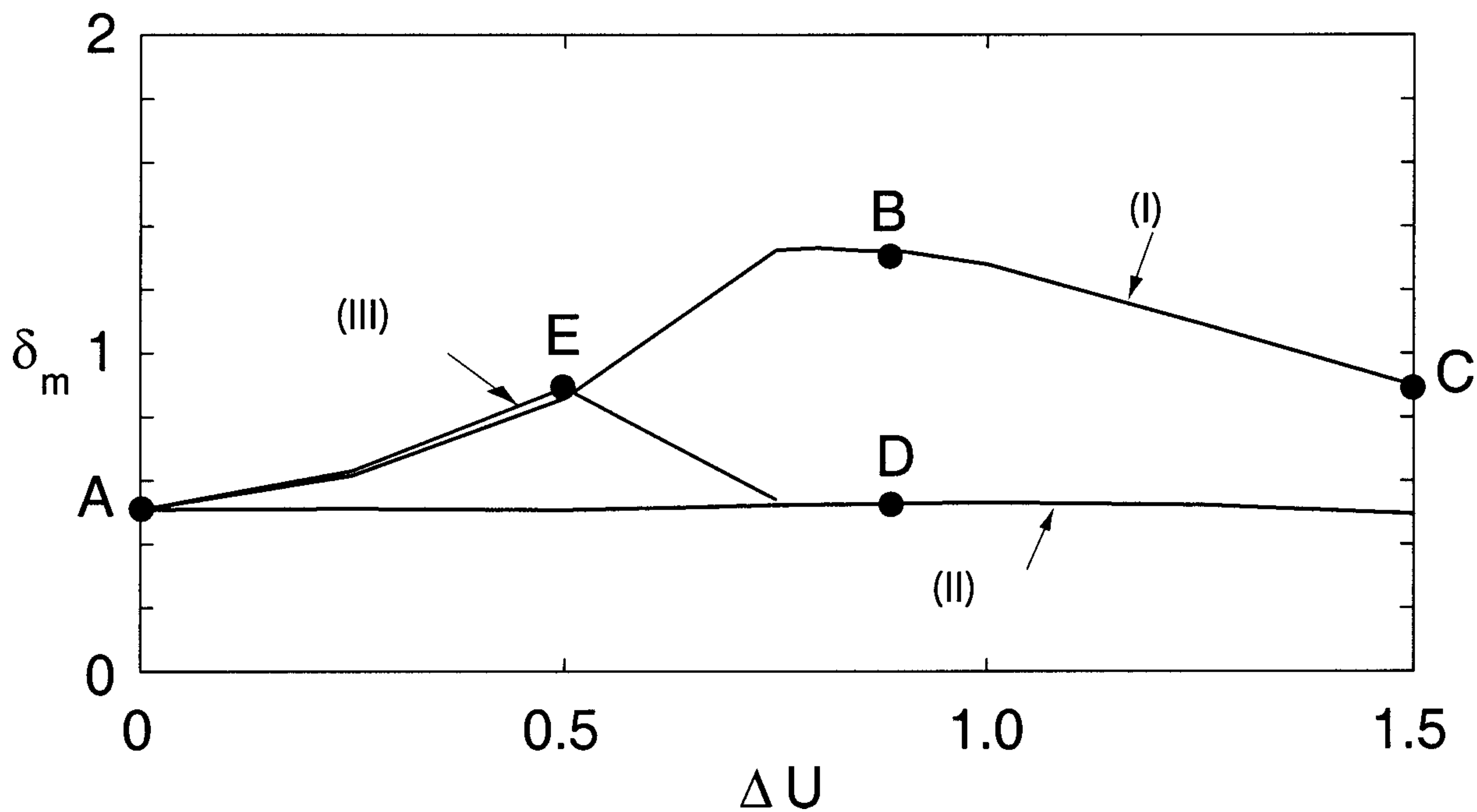
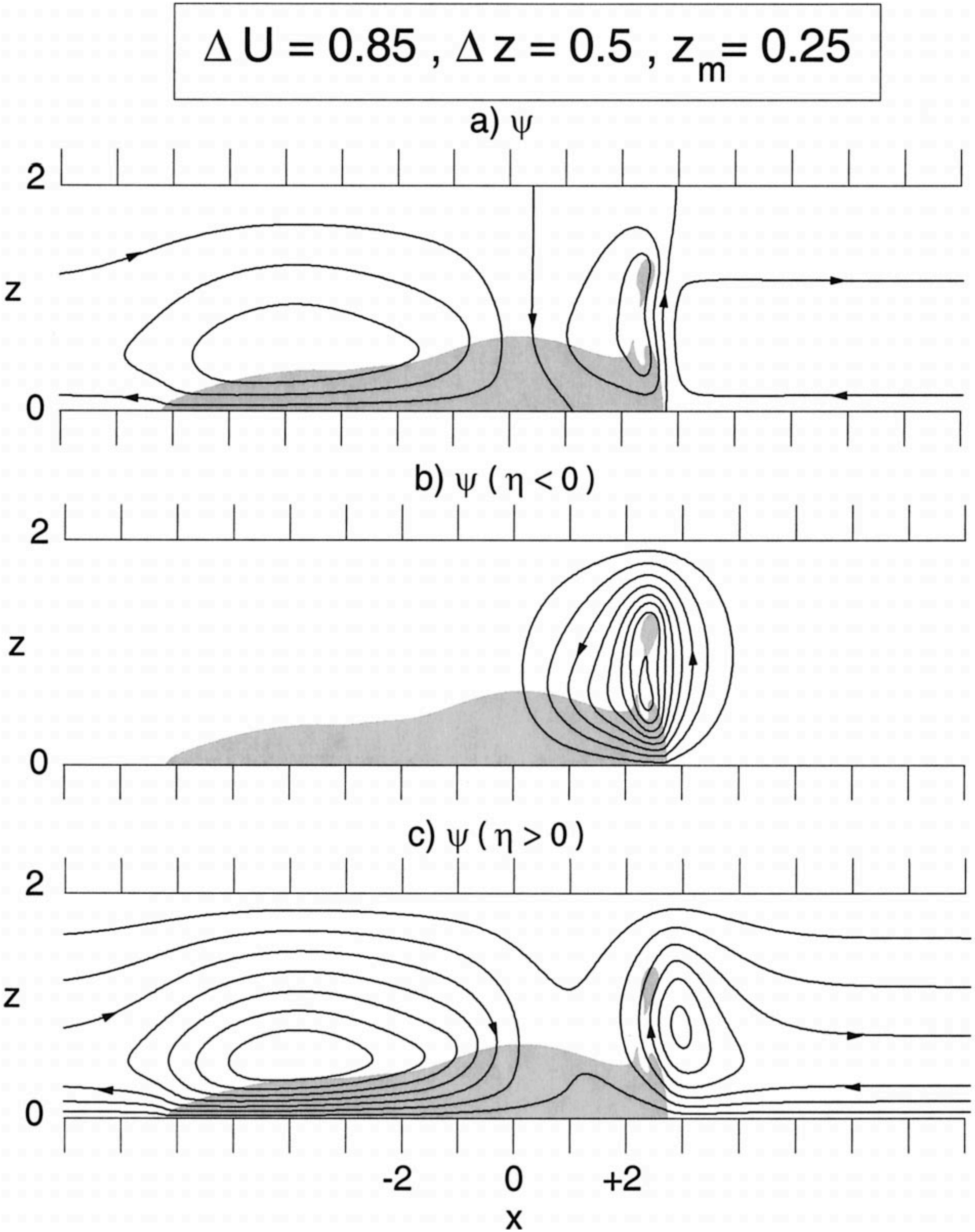


FIG. 5. The maximum displacement (d_m) of low-level (s , 0.5) air parcels at t 5 4 for all experiments. Letters indicate solutions displayed in Figs. 4 and 6–9. The three curves correspond to the shear profiles shown in Fig. 3b.

The argument is that the deepest lifting occurs when the circulation associated with the cold pool is nearly balanced with that of the low-level shear. By a simple control volume analysis RKW deduced that this balance occurs when

$$\Delta\tilde{U} = \sqrt{2\tilde{b}_0\tilde{h}_c} \equiv C, \tag{8}$$

where $\tilde{h}_c$ is the height of the cold pool. Examination of Fig. 6 shows that $\tilde{h}_c \approx \tilde{h}/2$, and so (8) gives $\sqrt{\tilde{b}_0\tilde{h}}/\Delta\tilde{U} = 1$, which is close to the experimentally determined value of 0.85 (Fig. 5).



total flow

flow induced by downshear cold pool

flow induced by shear layer and upshear cold pool

3D simulations

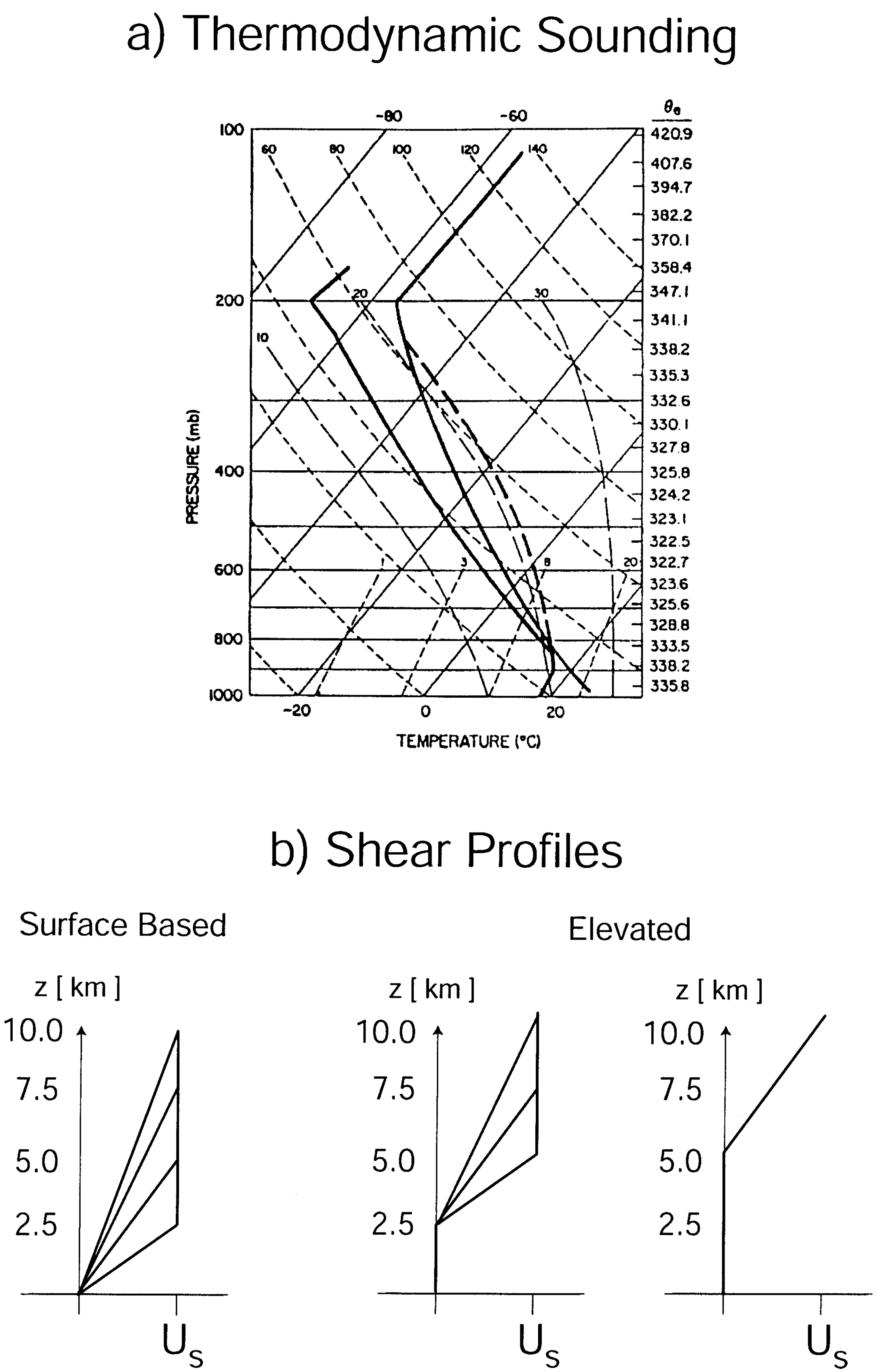
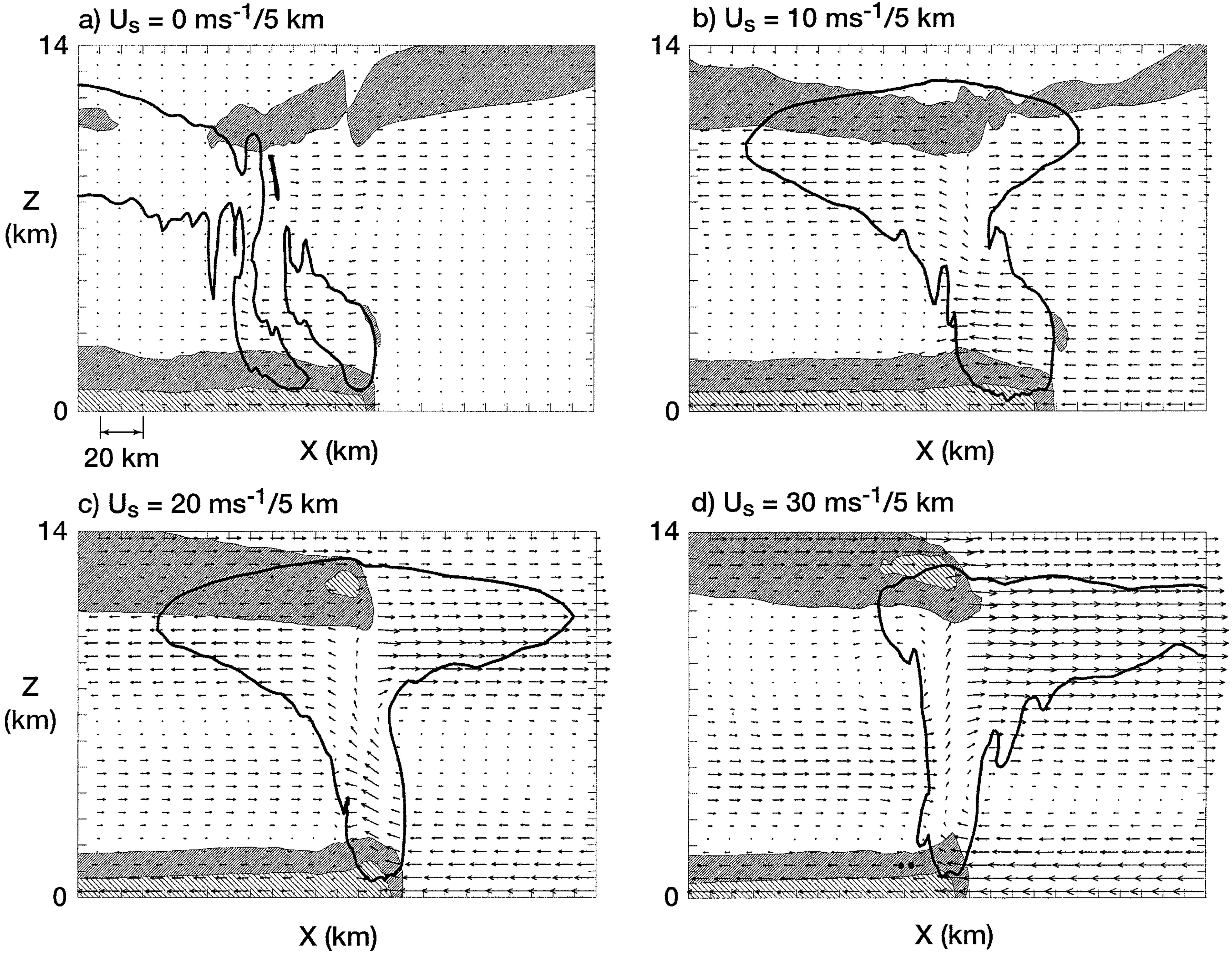
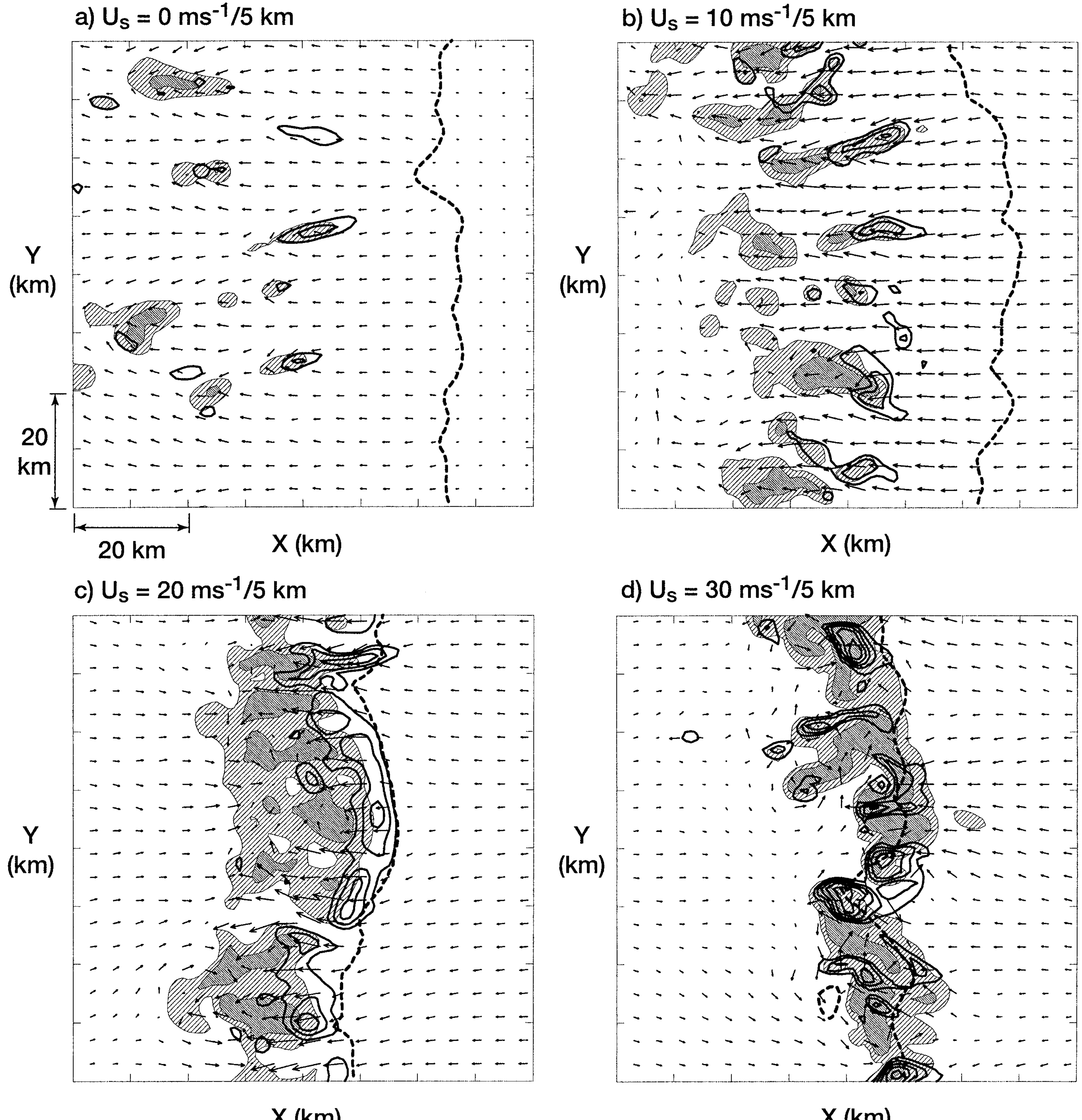


FIG. 11. (a) Thermodynamic sounding and (b) wind profiles used for simulations.



a) U_s = 0 ms^{-1}/5 km
b) U_s = 10 ms^{-1}/5 km
c) U_s = 20 ms^{-1}/5 km
d) U_s = 30 ms^{-1}/5 km
14
0
Z (km)
X (km)
20 km



a) U_s = 0 ms^{-1}/5 km
b) U_s = 10 ms^{-1}/5 km
c) U_s = 20 ms^{-1}/5 km
d) U_s = 30 ms^{-1}/5 km
Y (km)
X (km)
20 km
20 km

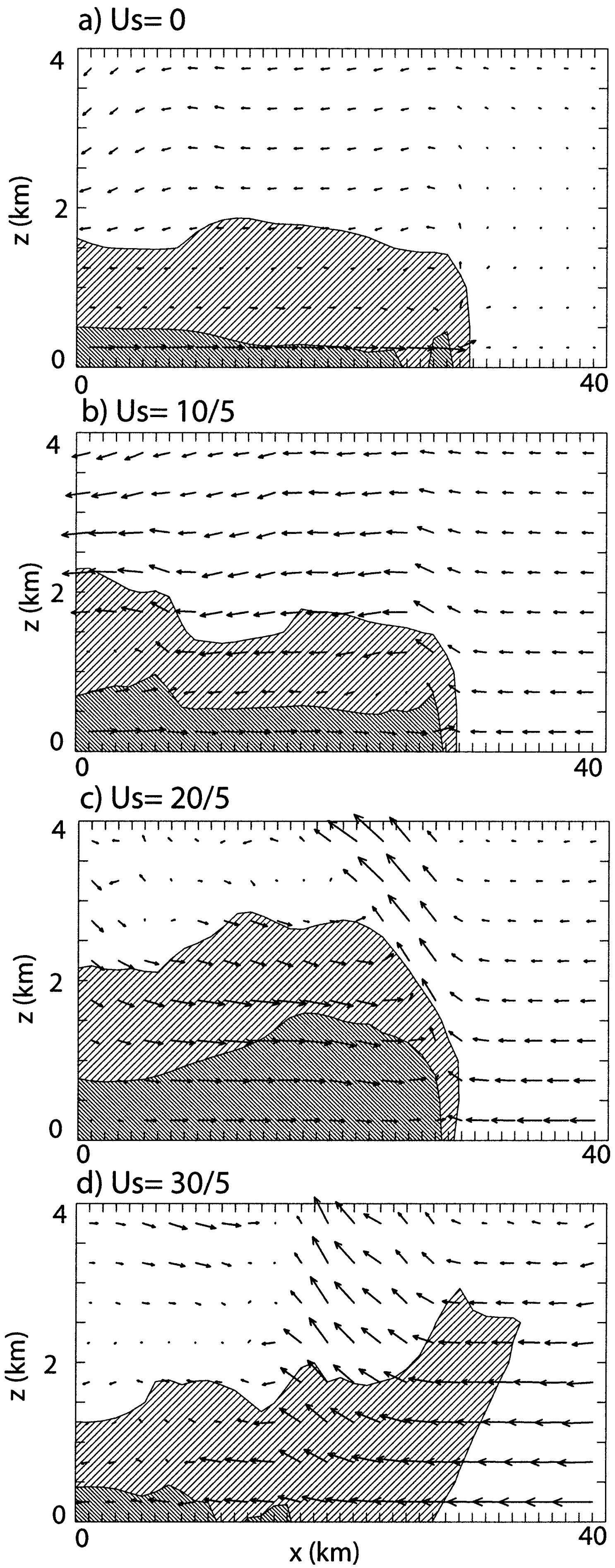


FIG. 14. Representative vertical cross section of system-relative flow vectors and negative buoyancy field through the cold pool for the (a) U_s 5 0 m s^{21}, (b) U_s 5 10 m s^{21}, (c) U_s 5 20 m s^{21}, and (d) U_s 5 30 m s^{21} 5-km-deep surface-based shear simulations at 4 h. Magnitudes of the buoyancy field between 20.015 and -0.15 m s^{-2} are lightly stippled, with magnitudes less than -0.15 m s^{-2} darkly stippled. Vectors are included every 2 km in the horizontal, and 500 m in the vertical, with a horizontal vector length of 2 km equal to vector magnitude of 15 m s^{-1}. Tick marks are included every 1 km in the horizontal and 500 m in the vertical. Only a 40 km × 4 km portion of the full domain is shown.