# Diabatic Processes

- Diabatic processes are non-adiabatic processes such as
  - precipitation fall-out
  - entrainment and mixing
  - radiative heating or cooling

# Parcel Model

$$\frac{d\theta}{dt} = \frac{L}{c_p\bar{\pi}}(C - E_r) + D_\theta$$

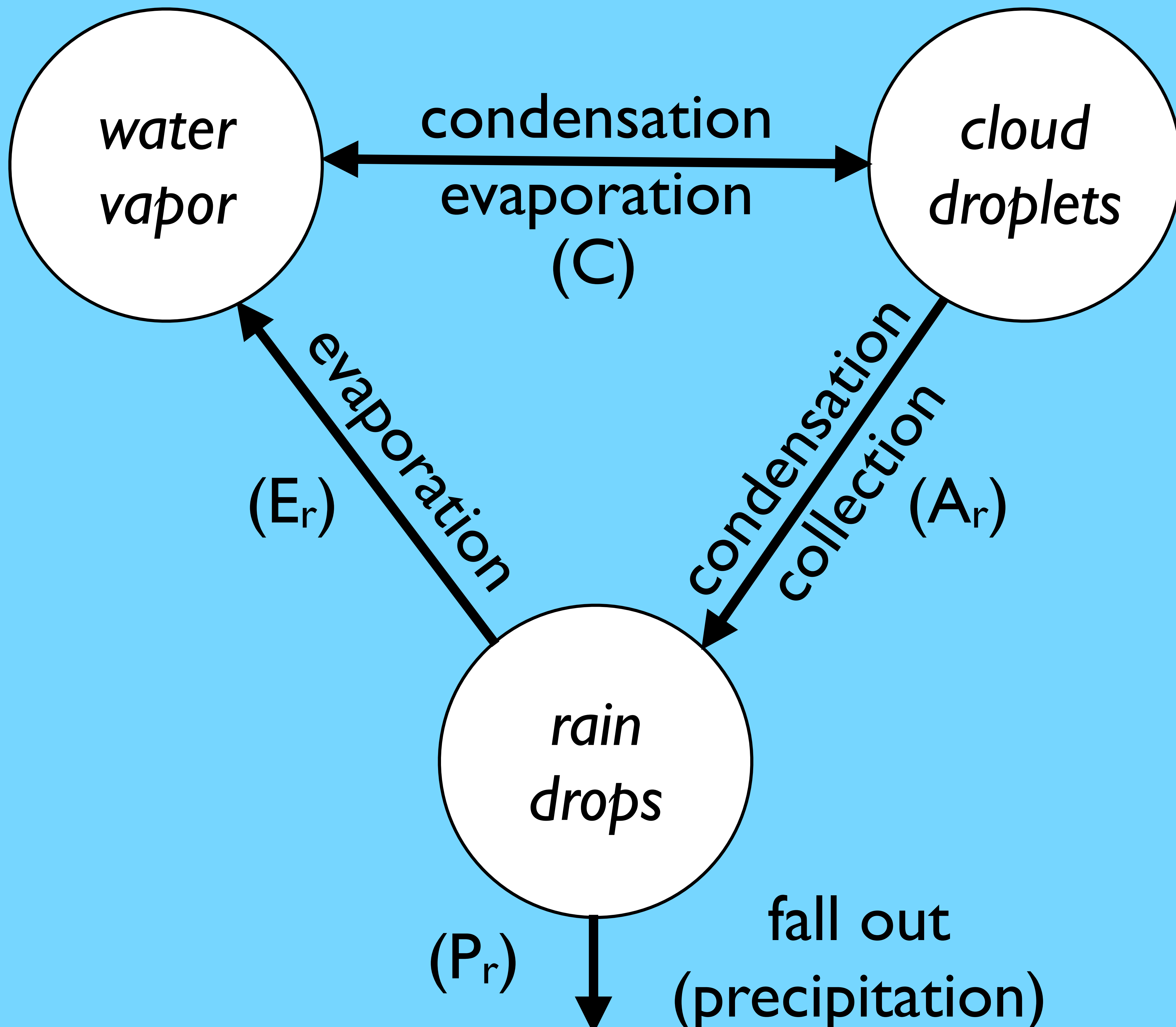
$$\frac{dw}{dt} = -(C - E_r) + D_w$$

$$\frac{dl}{dt} = C - A_r + D_l$$

$$\frac{dr}{dt} = P_r + A_r - E_r + D_r$$

$\bar{\pi} = (\bar{p}/p_0)^{R/c_p}$, $C$ is the net condensation rate, $E_r$ is the rain evaporation rate, $A_r$ is the cloud-to-rain water conversion rate, $P_r$ is the convergence of rain water flux, and $D_i$ represents the effects of entrainment and mixing.

# Microphysics



# Diabatic Processes

Process rates per unit time interval:

$$A_r \equiv \left(\frac{dl}{dt}\right)_{\text{conversion to rain}} = \left(\frac{dr}{dt}\right)_{\text{conversion from cloud water}}$$

Process rates per unit pressure interval:

$$-\frac{dl}{dp} = \hat{C} - \hat{A}_r + \hat{D}_l$$

$$-\hat{A}_r \equiv \left(-\frac{dl}{dp}\right)_{\text{conversion to rain}} = -Cl,$$

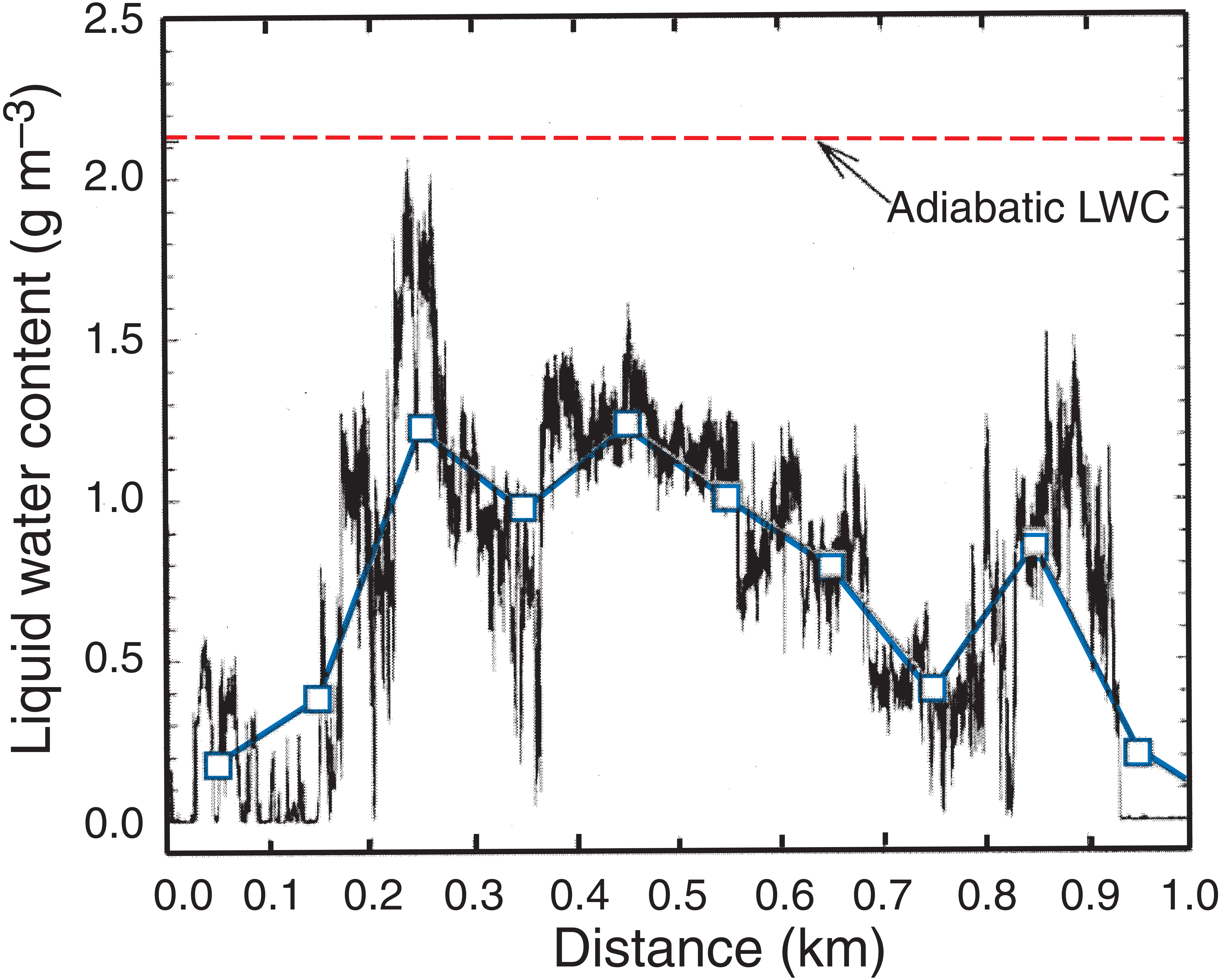
for $dp/dt < 0$ only, with $C = 2 \times 10^{-2}\ \text{mb}^{-1}$.

# Entrainment

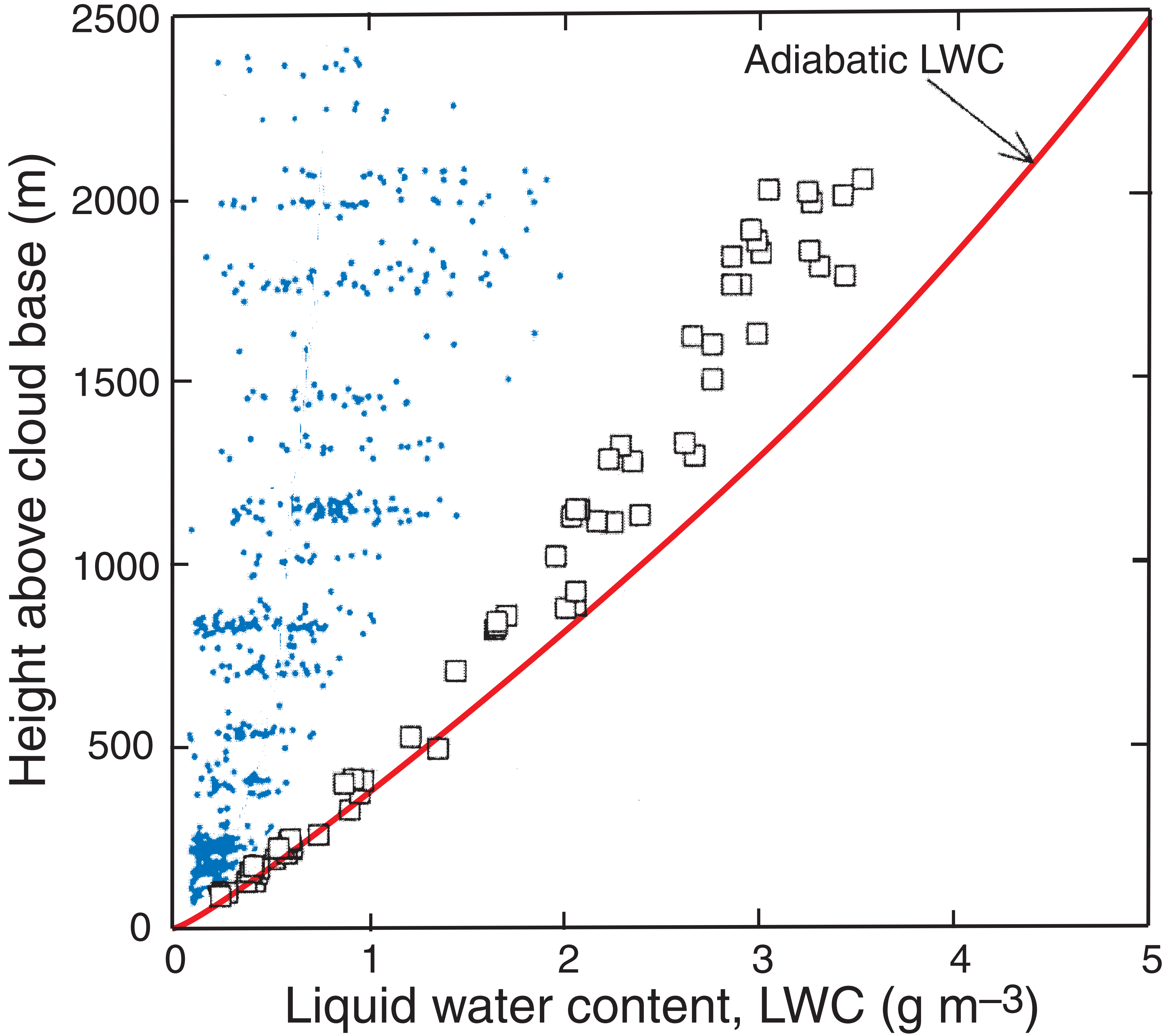
*Entrainment is the incorporation of environmental air into a parcel or cloud.*

FIG. 13. Illustration of entrainment and mixing in small cumulus clouds. Key characteristics: initial entrainment and mixing near edges, simultaneous but discrete large-scale entrainment events due to cloud-scale eddies, subsequent homogenization of regions 10–100 m in length.

# Evidence for Entrainment in Cu



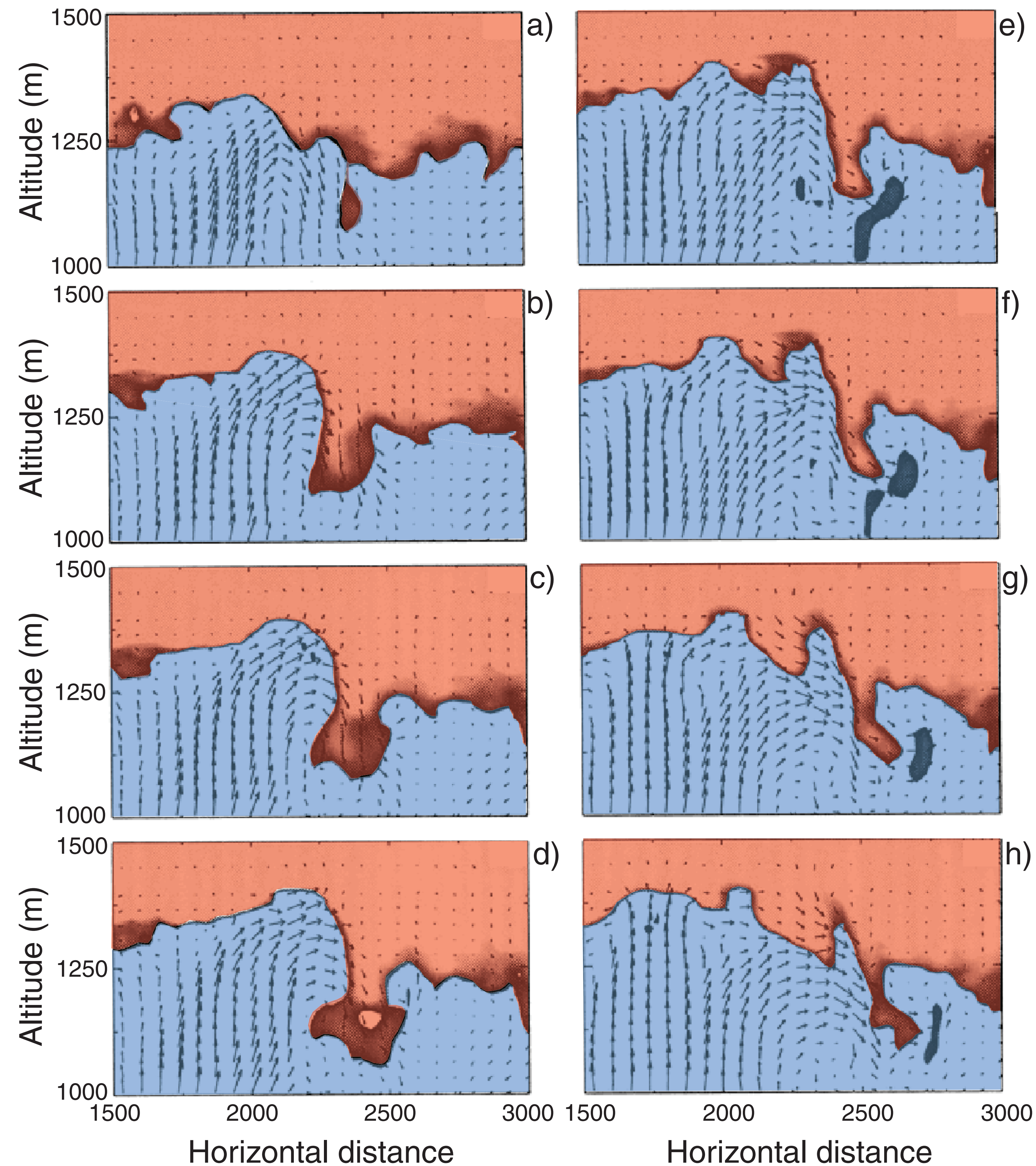
# Evidence for Entrainment in Cu



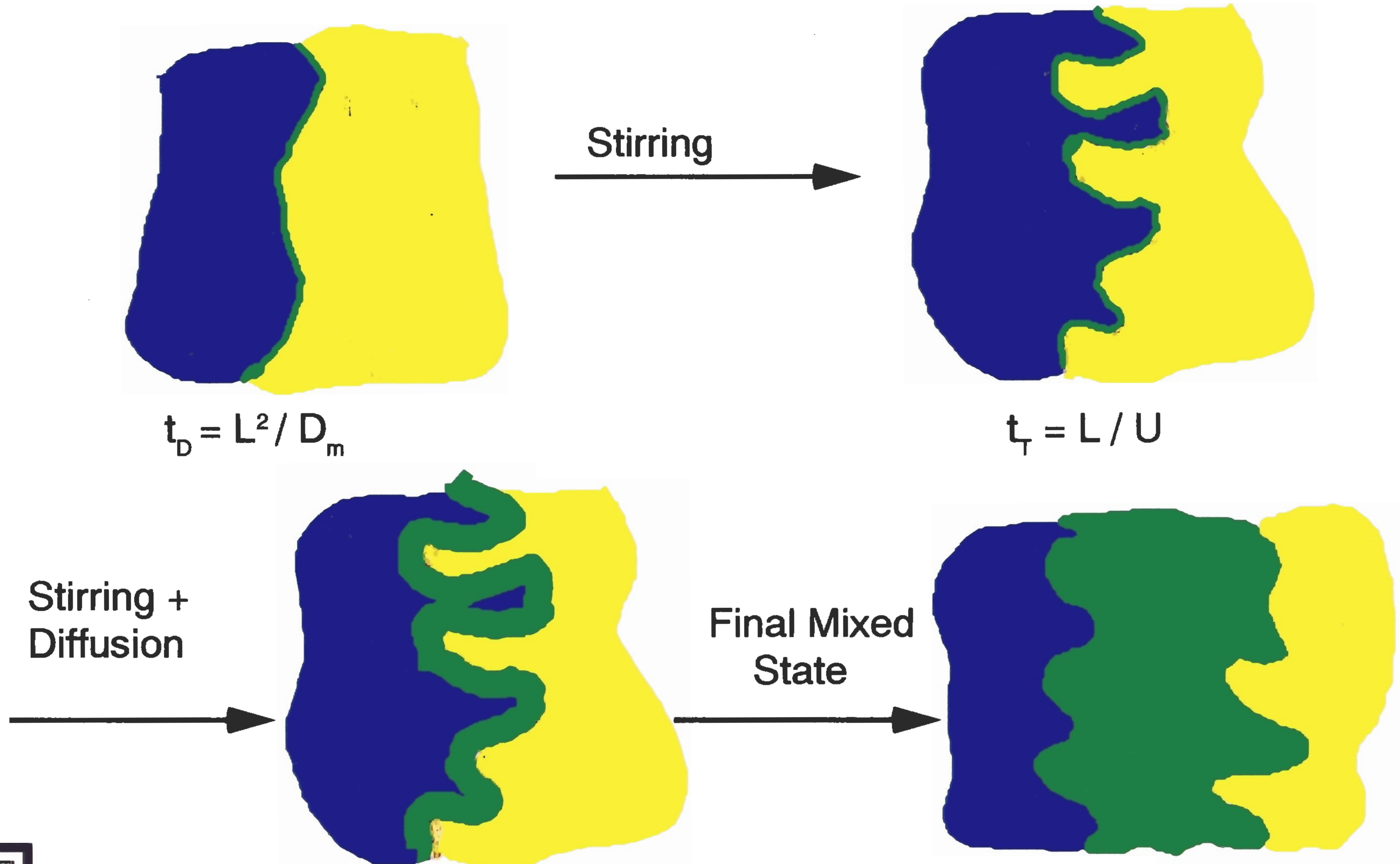
# Entrainment in Stratocumulus

# Entrainment in Stratocumulus

Entrainment in a 3D high-resolution simulation of Sc.

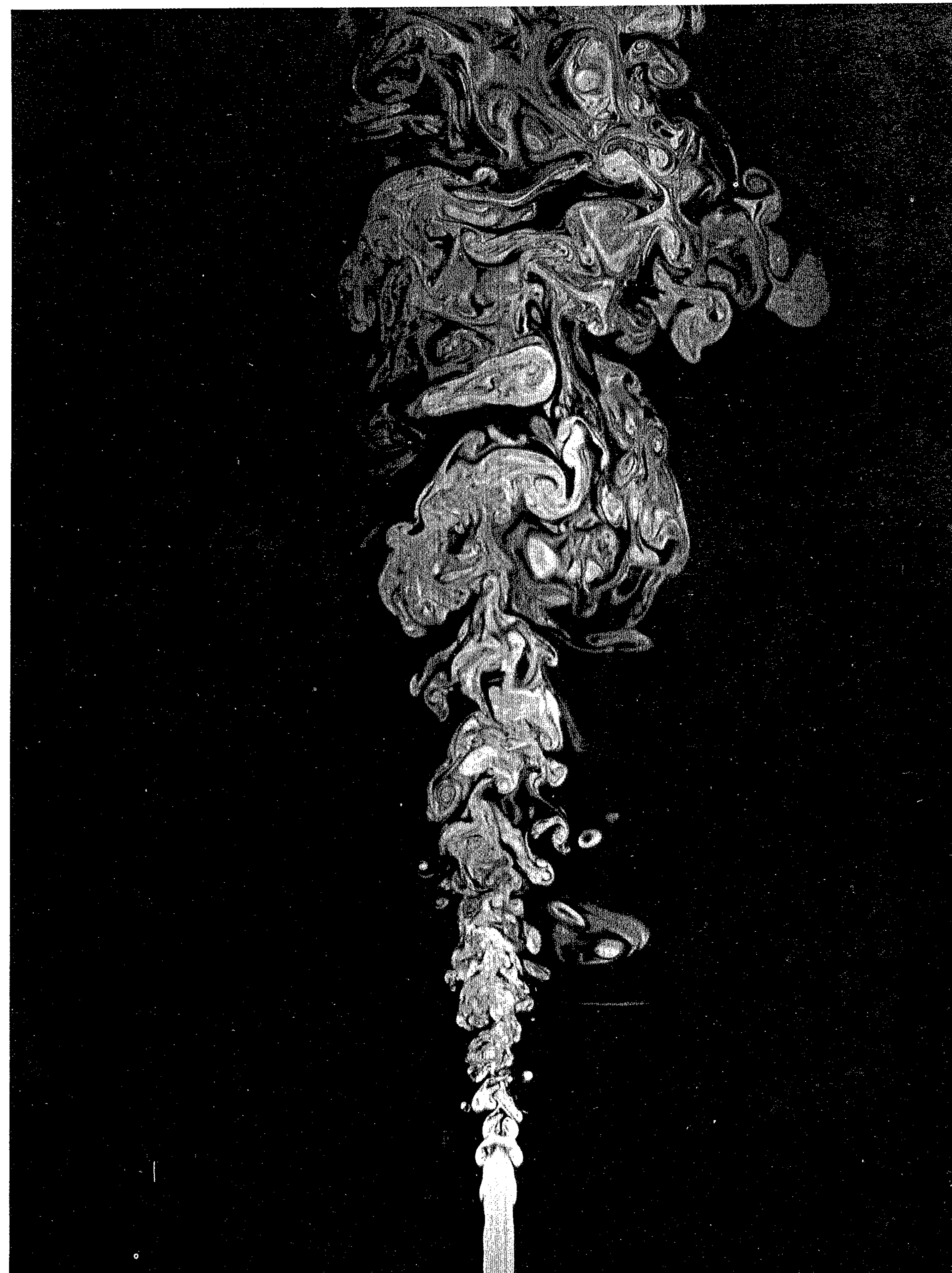


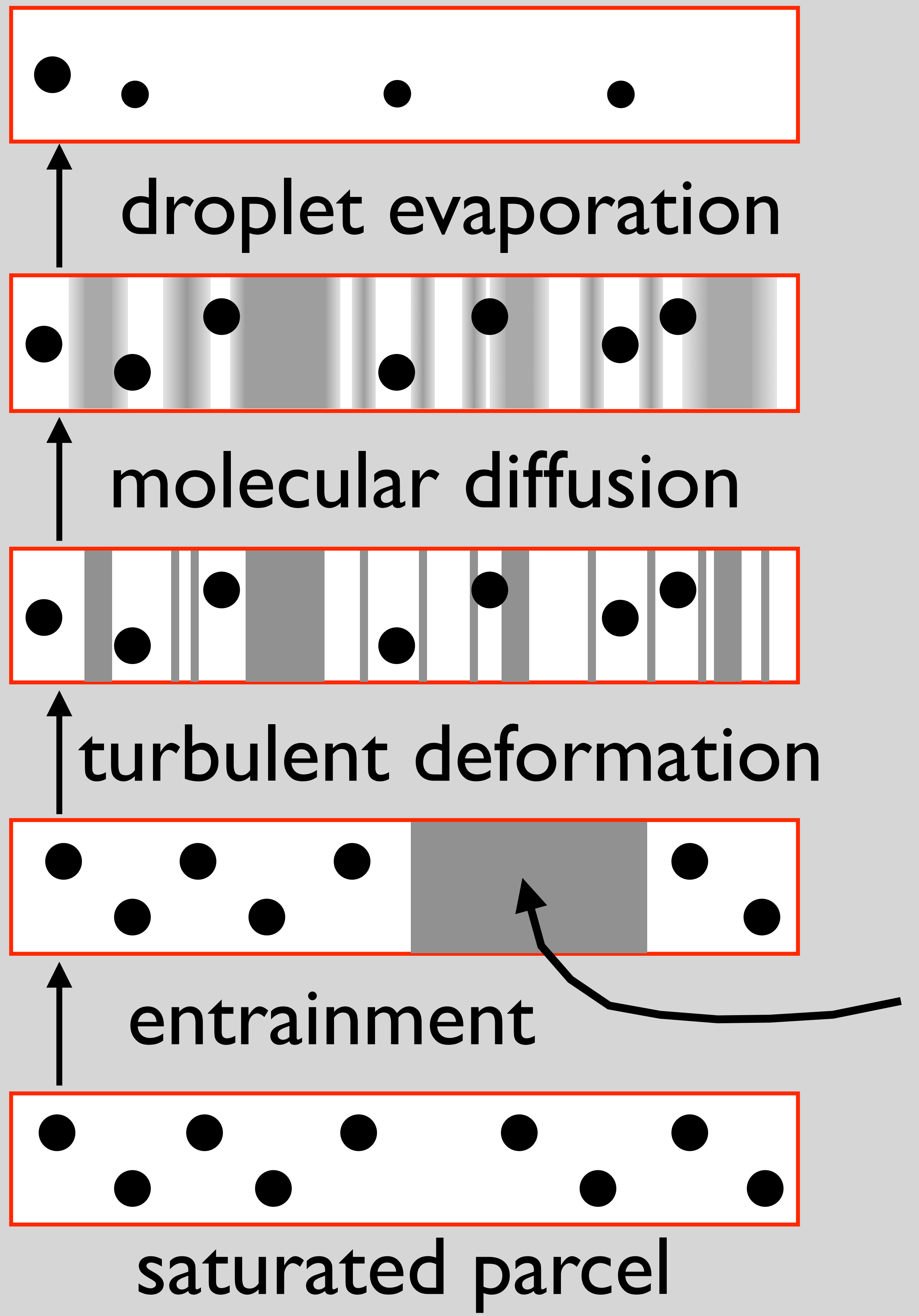
**Turbulent Mixing:** Process by which a fluid with two initially segregated scalar properties mix at the molecular level



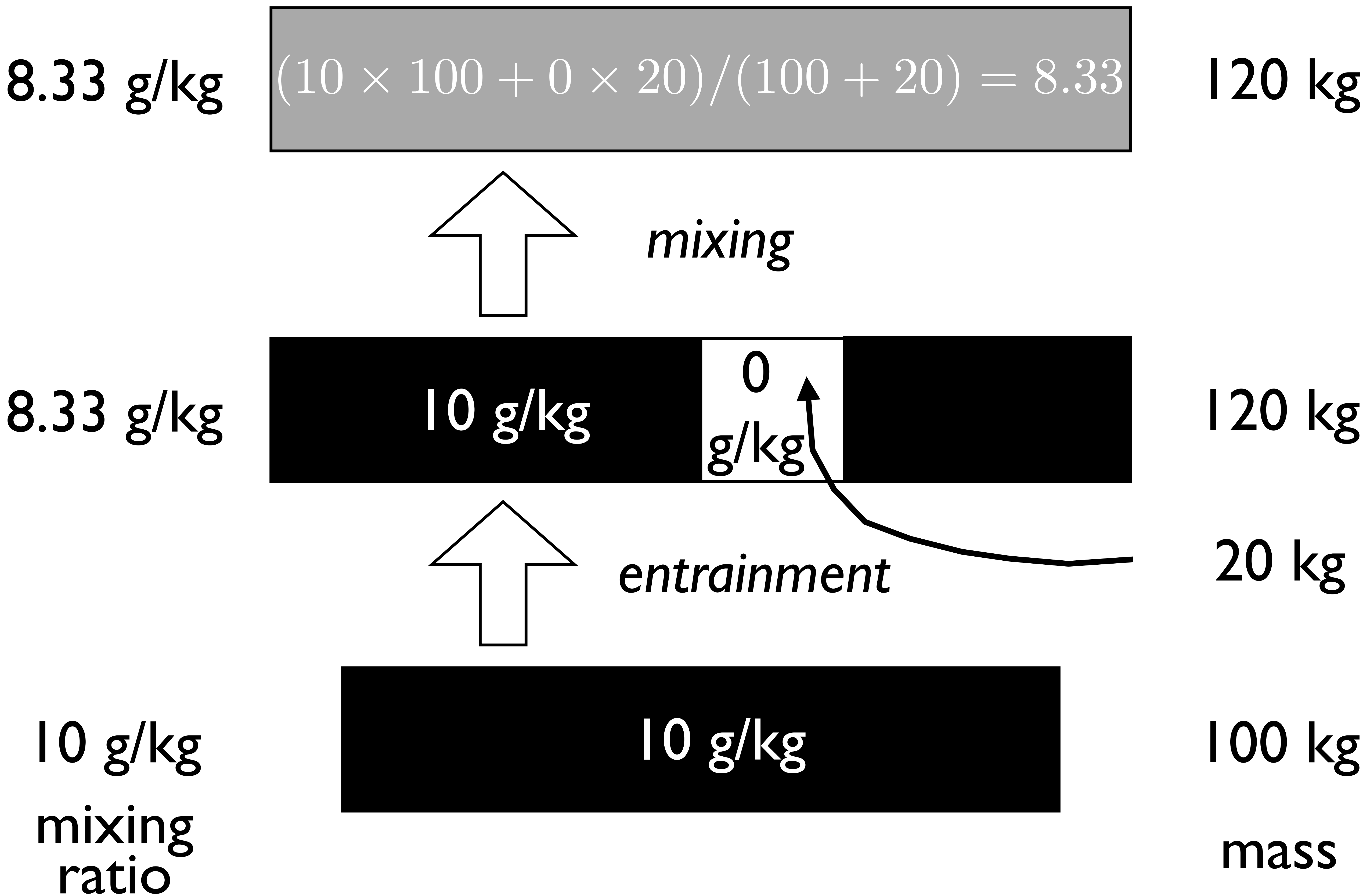
# Entrainment: Kelvin-Helmholtz Instability

# Entrainment into a turbulent jet




droplet evaporation
molecular diffusion
turbulent deformation
entrainment
saturated parcel

# Fractional Rate of Entrainment



# Entrainment

The *fractional rate of entrainment* of a parcel of mass $m$ that entrains a blob of mass $dm$ while the pressure changes by $-dp$ (due to ascent) is

$$\hat{\lambda} \equiv -\frac{1}{m}\frac{dm}{dp}.$$

The rate of change of a scalar $\phi$ due to entrainment is

$$\hat{D}_\phi \equiv \left(-\frac{d\phi}{dp}\right)_{\text{entrainment}} = -\hat{\lambda}(\phi - \phi_e),$$

where $\phi_e$ is the value of $\phi$ in the entrained air.

# Entrainment

We can derive this from

$$\left(-\frac{d\phi}{dp}\right)_{\text{entrainment}} = \lim_{\Delta p \to 0} \frac{\phi_{\text{after ent}} - \phi_{\text{before ent}}}{-\Delta p}$$

using

$$\phi_{\text{before ent}} = \phi$$

and

$$\phi_{\text{after ent}} = \frac{m\phi + \Delta m\ \phi_e}{m + \Delta m}.$$

Substitution gives

$$\begin{aligned}\left(-\frac{d\phi}{dp}\right)_{\text{entrainment}} &= \lim_{\Delta p \to 0} \frac{1}{m + \Delta m} \frac{\Delta m}{\Delta p}(\phi - \phi_e) \\ &= \frac{1}{m} \frac{dm}{dp}(\phi - \phi_e) = -\hat{\lambda}(\phi - \phi_e).\end{aligned}$$

# Entrainment

$$
\begin{aligned}
\hat{D}_\theta &= -\lambda(\theta - \theta_e), \\
\hat{D}_w &= -\lambda(w - w_e), \\
\hat{D}_l &= -\lambda(l - l_e) = -\lambda l.
\end{aligned}
$$

# Entrainment

- In cumulus clouds, the fractional rate of entrainment, $\lambda \equiv (1/m)\,dm/dz$, ranges from about 0.1 $\text{km}^{-1}$ to 2 $\text{km}^{-1}$.

- Cloud-top height is largely determined by $\lambda$: deep clouds are associated with small values, and shallow clouds with large values.

- Field studies suggest that $\lambda \sim 0.2/R$, where $R$ is the cloud radius.

# Entrainment