Orographic Precipitation II:

Effects of Phase Change on Orographic Flow

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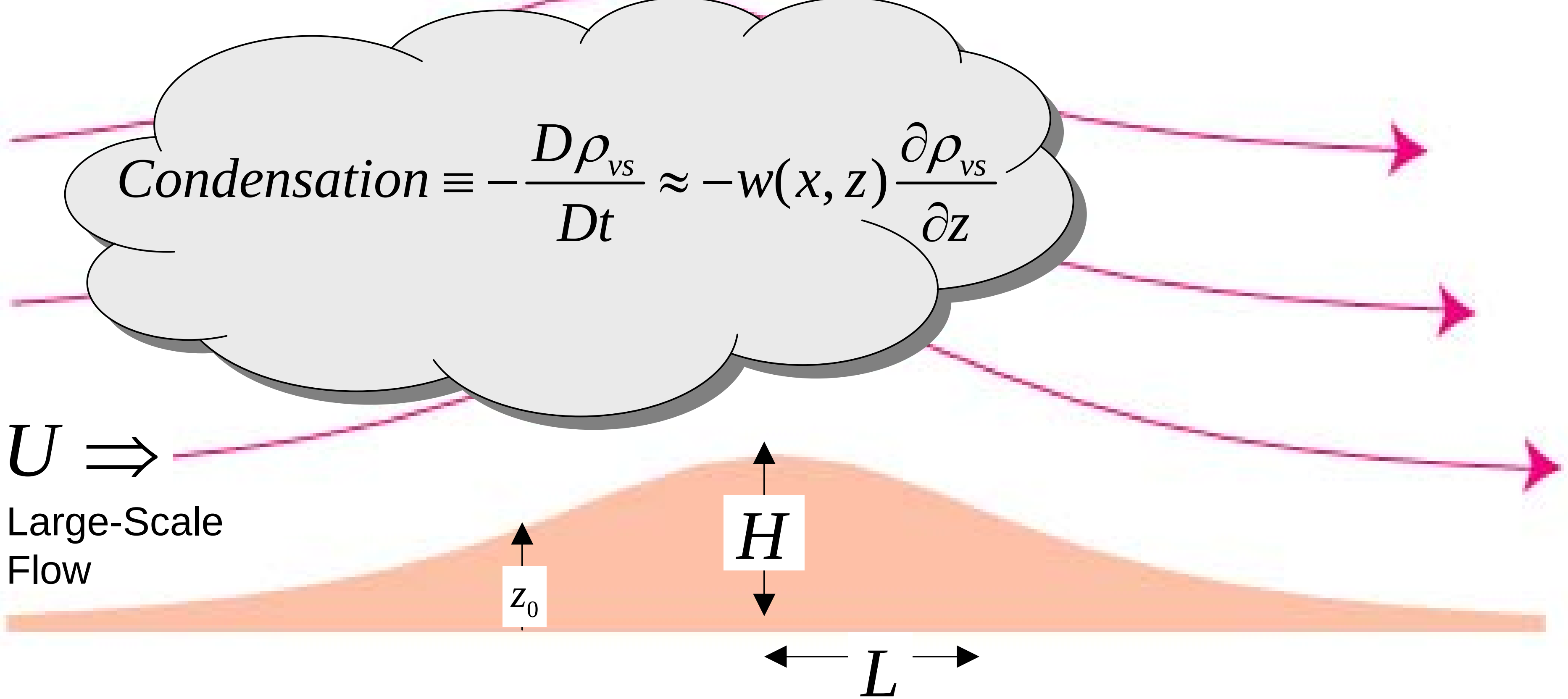
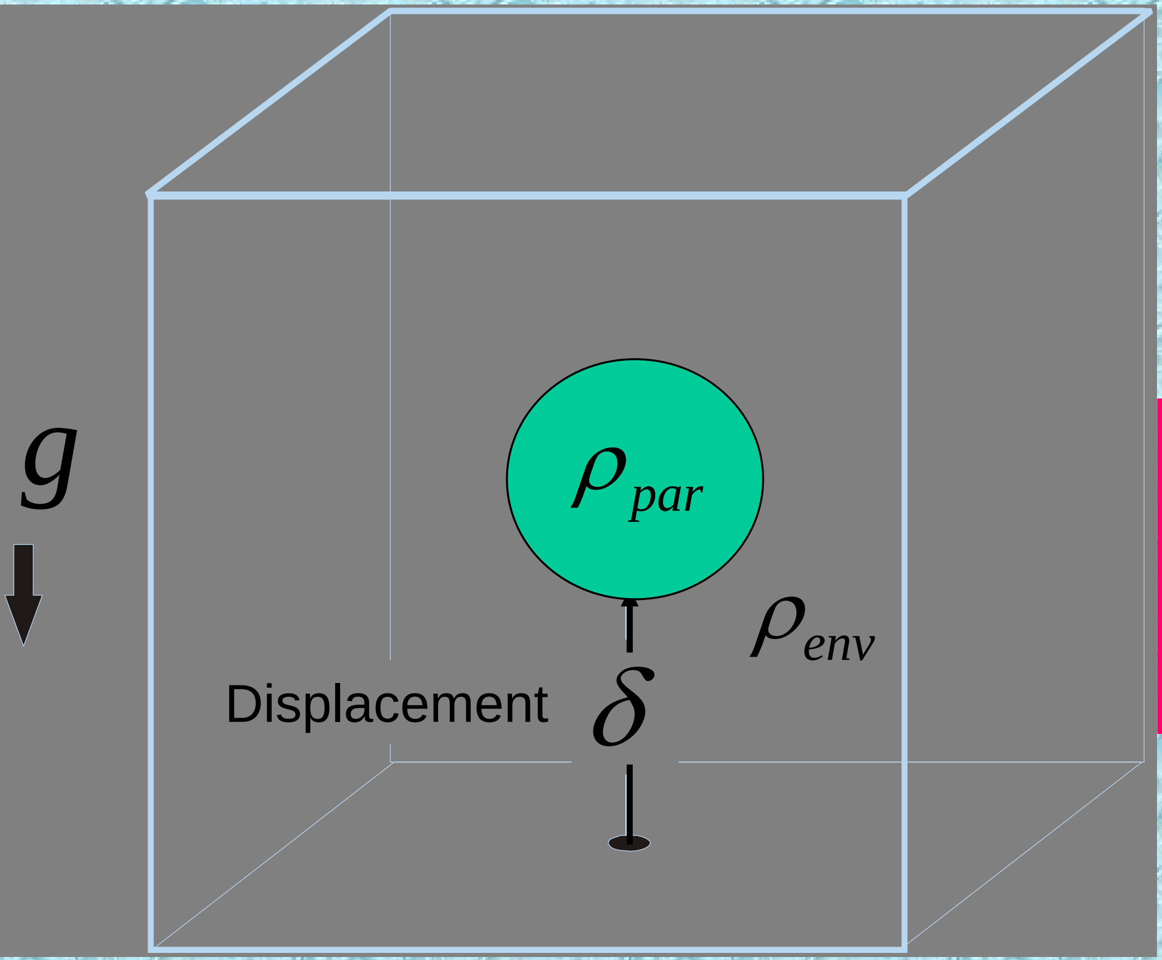


Dynamics→

$$w = w(H, L, U, Stability, Coriolis, 3D\ Effects)$$

ρ_{vs} = saturation vapor density

Effects of Water in the Air on Buoyancy



$$B = g \frac{\rho_{env} - \rho_{par}}{\rho_{par}}$$

ρ = density
"env" = environment
"par" = parcel

moist air is a mixture

$$\rho = \rho_d + \rho_v + \rho_l$$

gas law

$$p = (\rho_d R_d + \rho_v R_v)T$$

/ definitions

$$\varepsilon \equiv \frac{R_d}{R_v} \; ; \; q_v \equiv \frac{\rho_v}{\rho_d} \; ; \; q_w \equiv \frac{\rho_v + \rho_l}{\rho_d}$$

gas law

$$p = \rho R_d \left(\frac{1 + q_v \varepsilon^{-1}}{1 + q_w} \right) T \equiv \rho R_d \breve{T}$$

ρ = density
subscript d = dry air
subscript v = water vapor
subscript l = liquid water

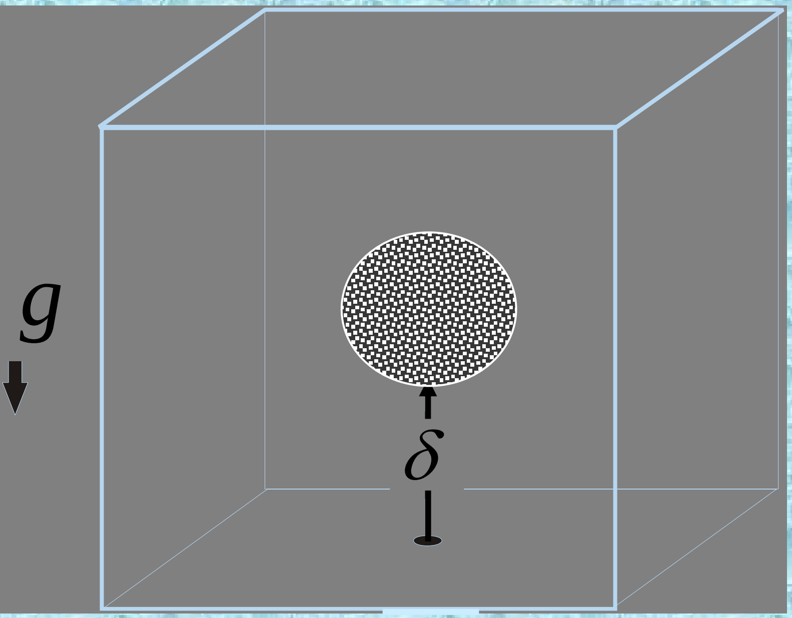
substitute $\breve{T}$ for ρ

$$B = g\,\frac{\breve{T}_{par} - \breve{T}_{env}}{\breve{T}_{env}}$$

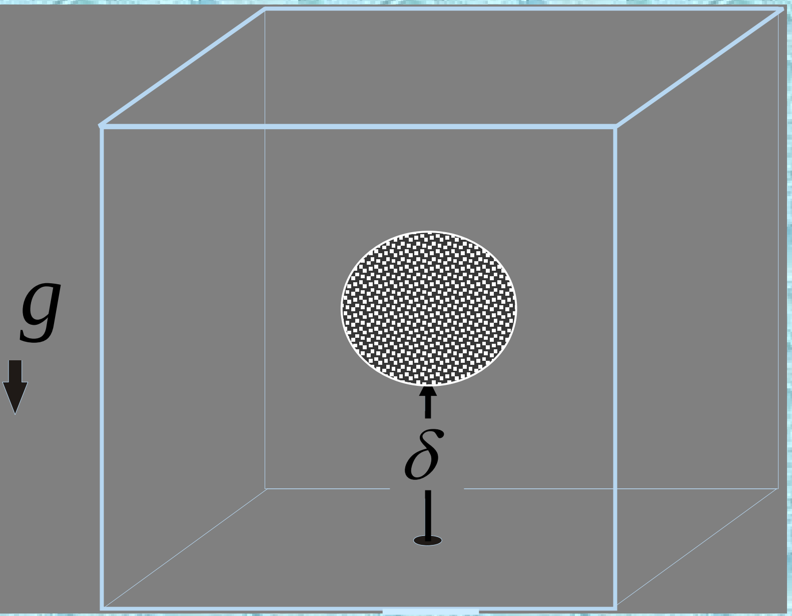
$$\breve{T} = \left(\frac{1 + q_v \varepsilon^{-1}}{1 + q_w}\right) T \cong \left(1 + 0.61 q_v - q_l\right) T$$

water vapor less dense than air

liquid water more dense than air



Main Effect on Buoyancy through Phase Change



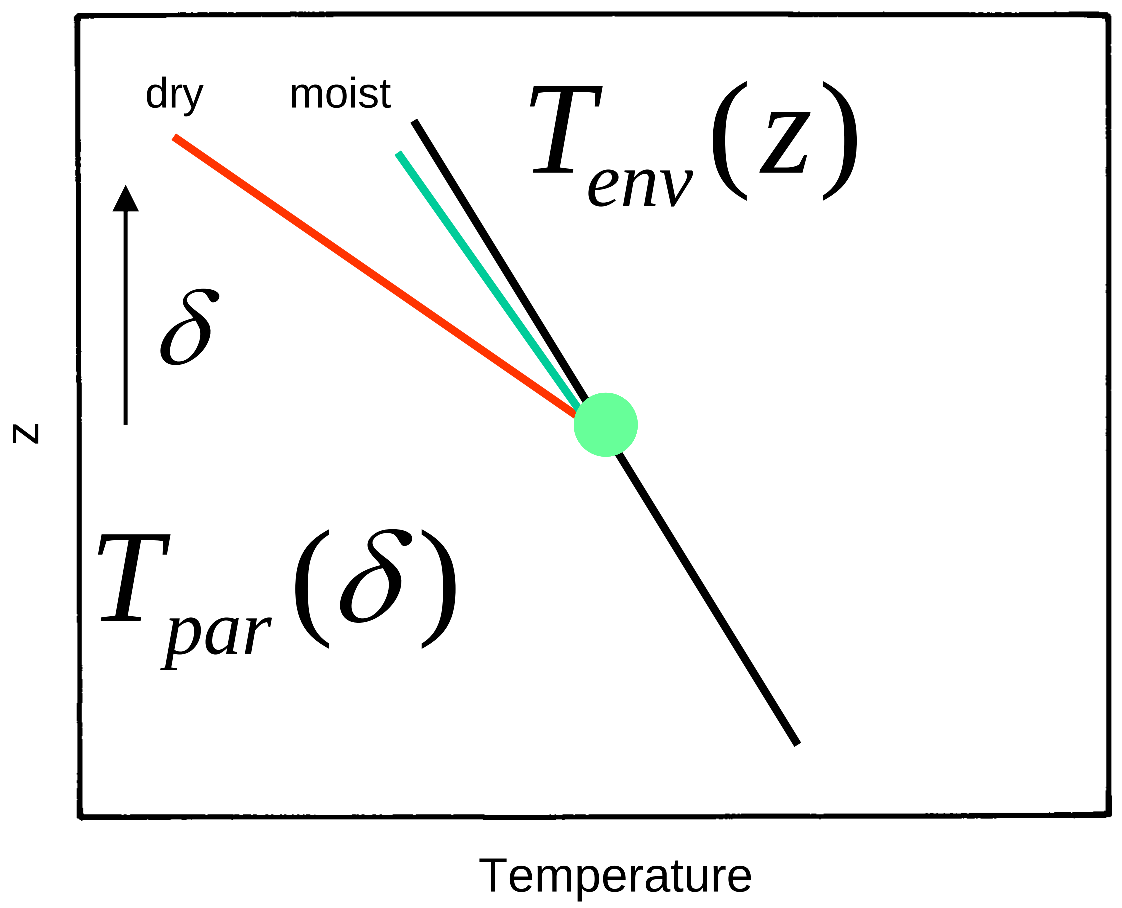
1st Law of Thermodynamics

$$c_p \frac{DT}{Dt} - \frac{1}{\rho}\frac{Dp}{Dt} = \frac{DQ}{Dt} = -L\frac{Dq_{vs}}{Dt}$$

condensation → latent heat release

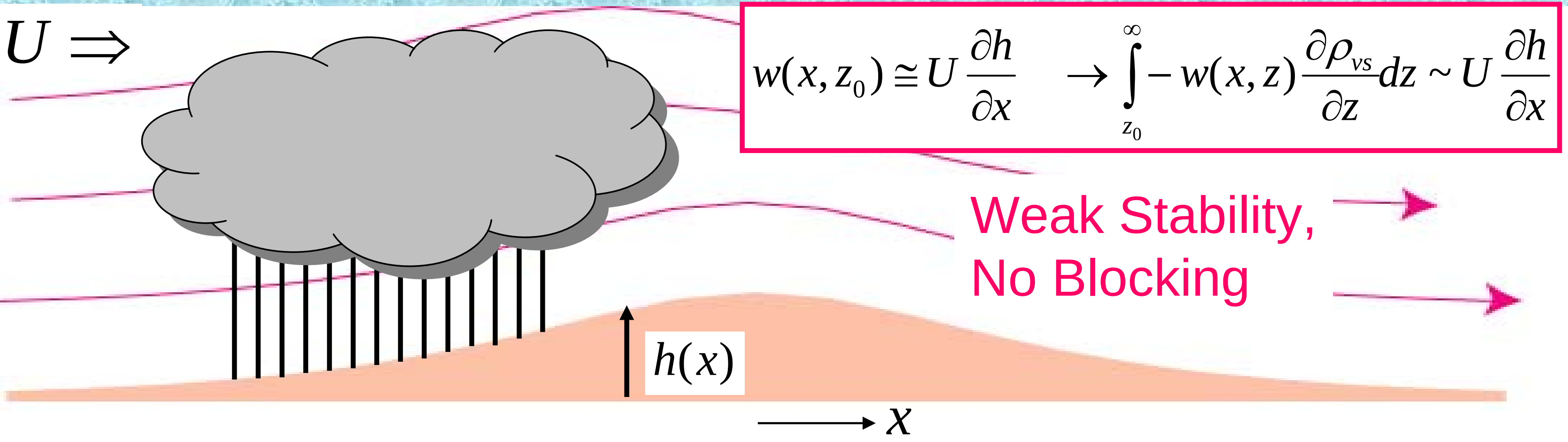
$$L \cong 600\, cal\, g^{-1}$$
$$c_p = .24\, cal\, g^{-1}\, {}^{\circ}C^{-1}$$
$$\Delta q_{vs} = -1\, g\, Kg^{-1} = -.001 \Rightarrow \Delta T \cong 2.5\, {}^{\circ}C$$

Air Parcel Behavior with Phase Change

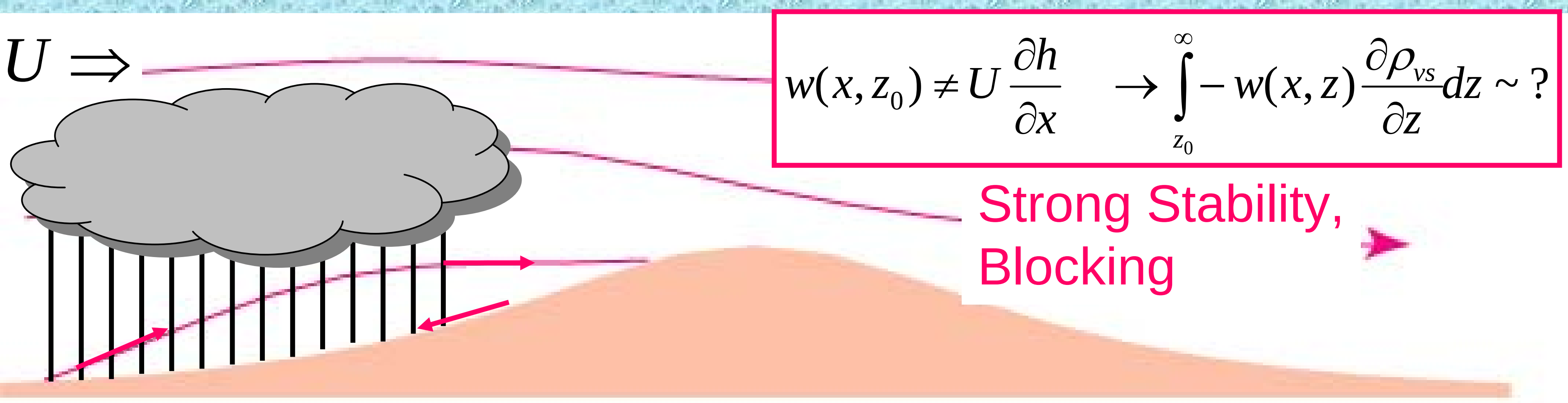


Latent Heat Release Reduces Stability

Dynamics:Stable Flow

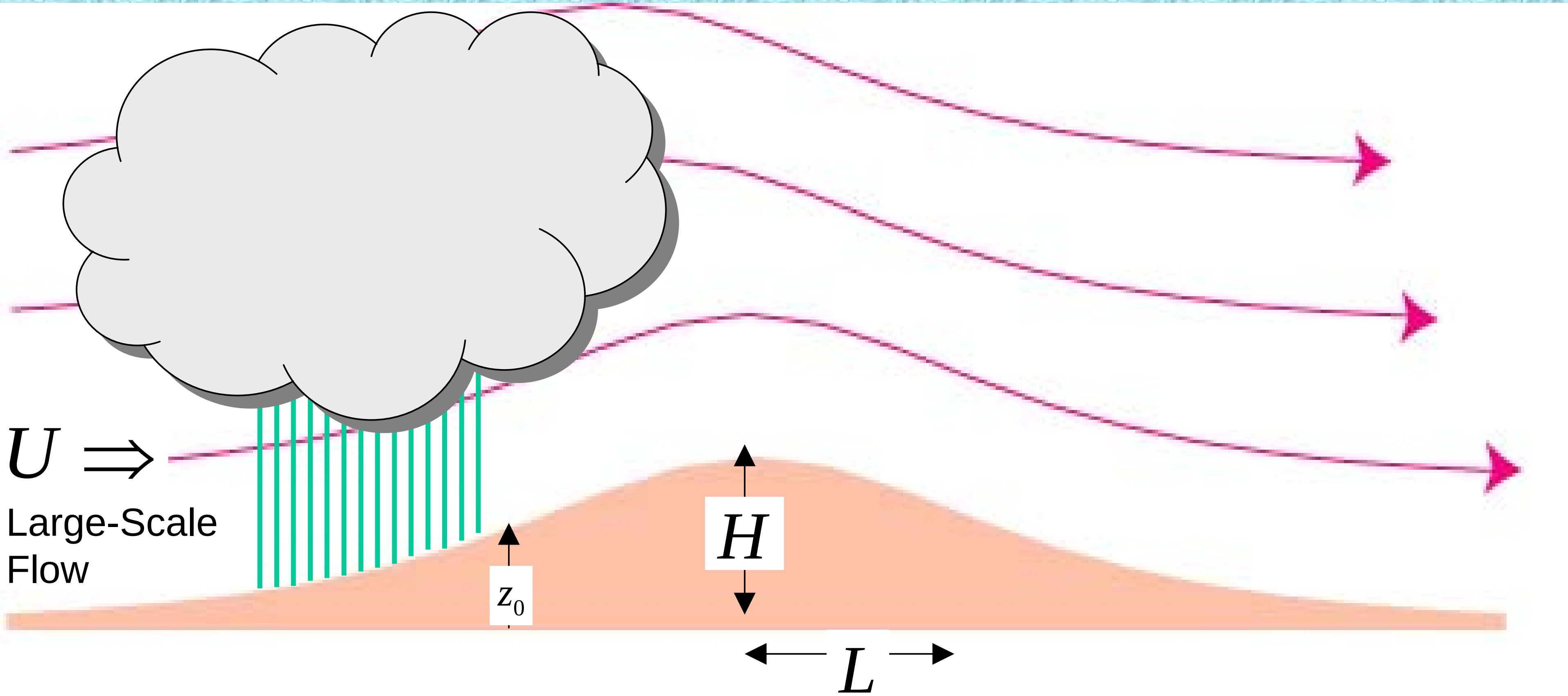


$$w(x,z_0) \cong U\frac{\partial h}{\partial x} \quad \rightarrow \int_{z_0}^{\infty} -w(x,z)\frac{\partial \rho_{vs}}{\partial z}dz \sim U\frac{\partial h}{\partial x}$$



$$w(x,z_0) \neq U\frac{\partial h}{\partial x} \quad \rightarrow \int_{z_0}^{\infty} -w(x,z)\frac{\partial \rho_{vs}}{\partial z}dz \sim ?$$

Weak Stability, No Blocking



Simplest Model→ Rainout = Condensation

$$R(x) = \int_0^\infty -w(x,z)\frac{\partial \overline{\rho}_{vs}}{\partial z}dz$$

Simple Model Overestimates R

$$\frac{d\rho_{liq}}{dt} = \frac{d(\rho_c + \rho_r)}{dt} = -\frac{d\rho_{vs}}{dt} + \frac{\partial R}{\partial z}$$

Introduce Time Lags

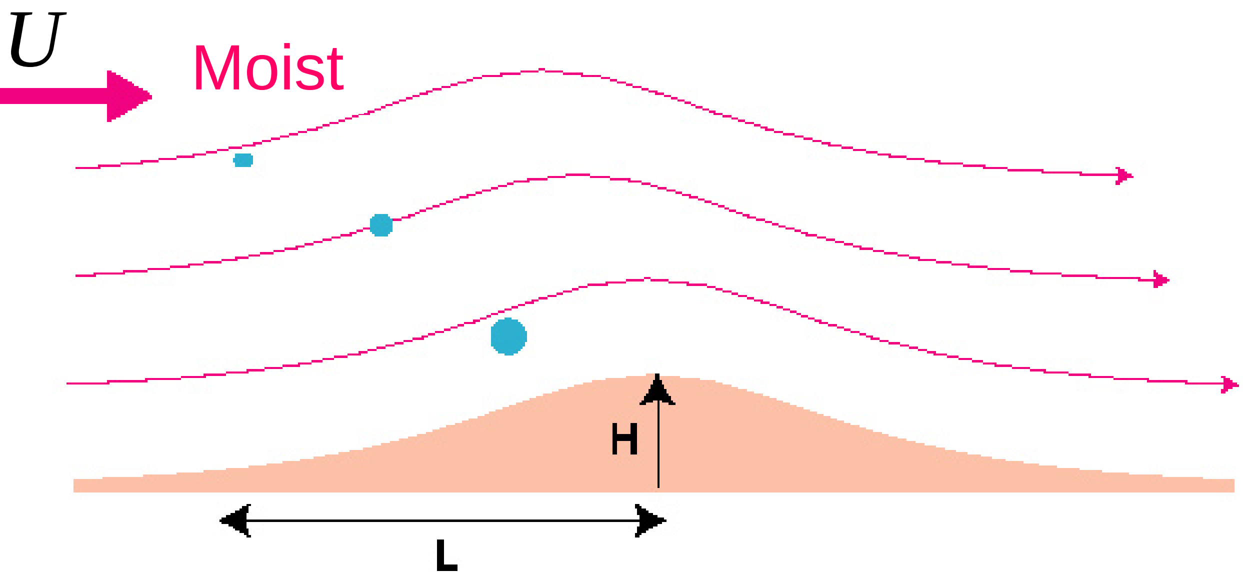
$$\frac{d\rho_c}{dt} = -\frac{d\rho_{vs}}{dt} - \frac{\rho_c}{\tau_c}$$

Conversion from Cloud droplets to Raindrops

$$\frac{d\rho_r}{dt} = +\frac{\rho_c}{\tau_c} - \frac{\rho_r}{\tau_r}$$

Precipitation

Smith and Barstaad (2004)



$$\tau_{microphysics} \ll \tau_{airflow}$$

$$1000s \ll \frac{L}{U}$$

$$U = 10m/s$$

L	L/U
$100km$	$10000s$
$10km$	$1000s$

$$\tau_{microphysics} \sim \tau_c + \tau_r$$

Transfer Function

Transform of precipitation field

Terrain transform

$$\hat{R}(k,l) = \frac{C_w i\sigma \hat{h}(k,l)}{[1 - i m \lambda_\rho][1 + i\sigma\tau_c][1 + i\sigma\tau_r]}$$

$$\sigma = Uk + Vl$$

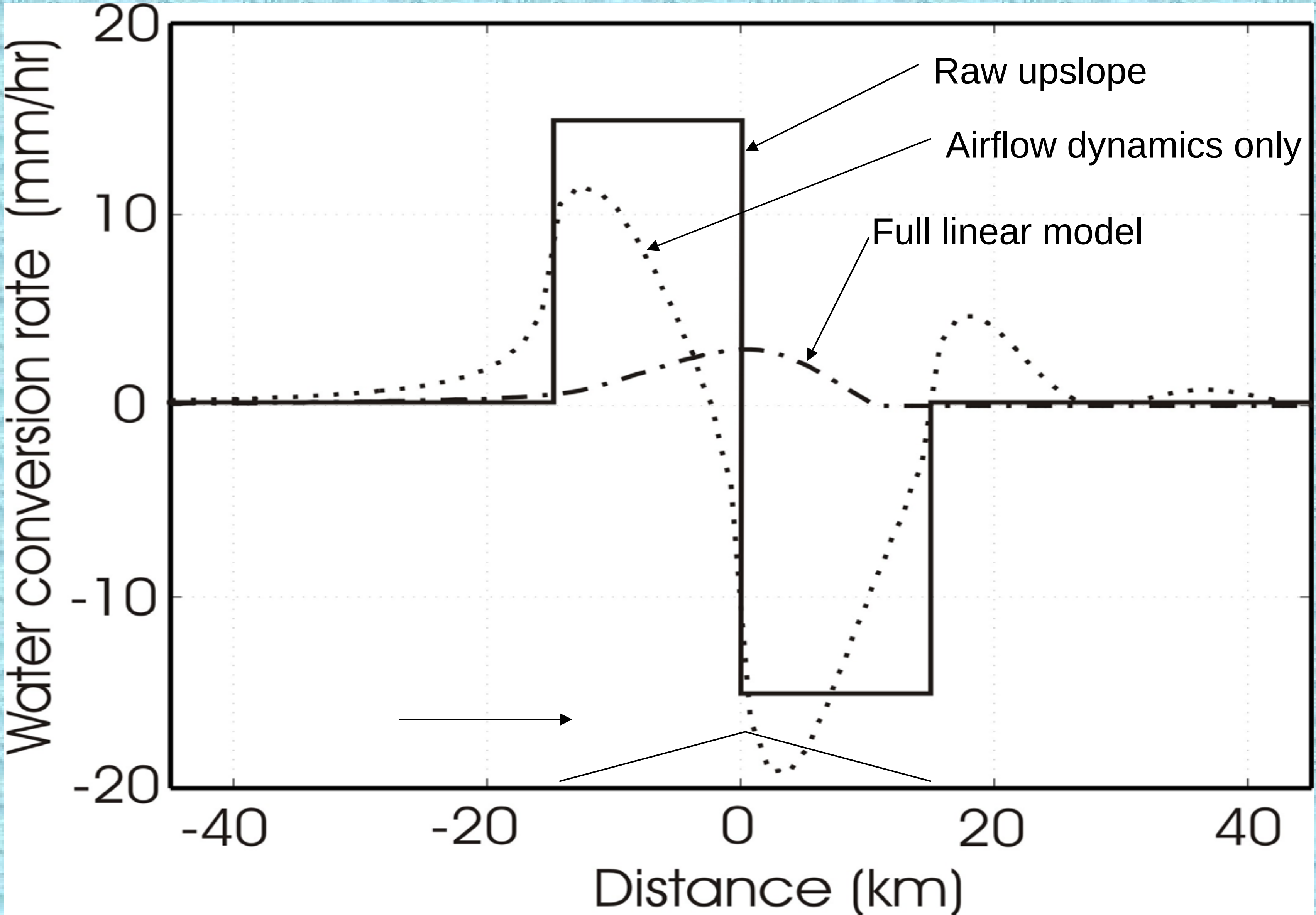
Airflow dynamics:
Uplift penetration

Cloud physics:
conversion

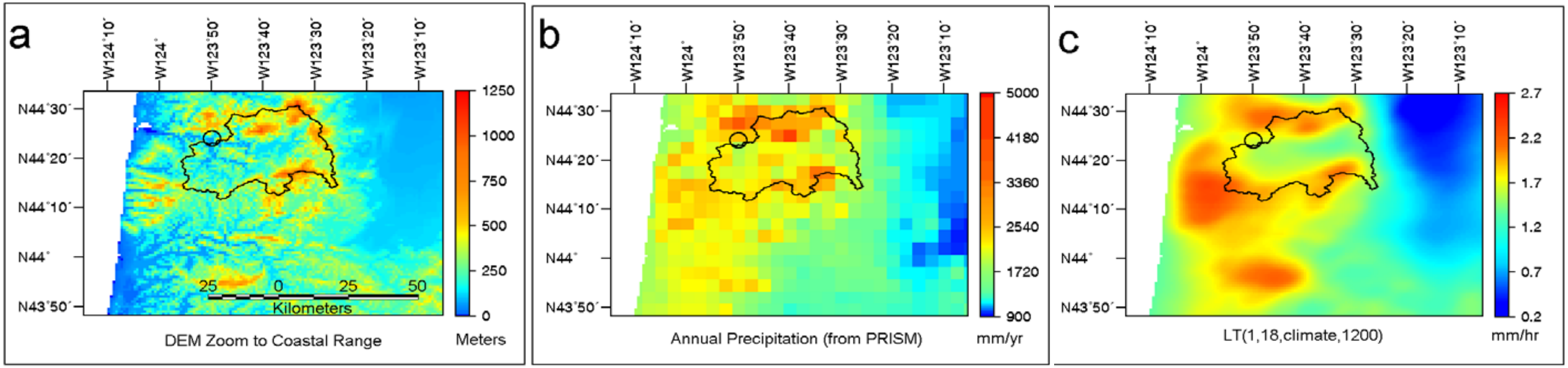
Cloud physics:
fallout

Each bracket shifts and reduces precipitation

Triangle Ridge: Three models



- With Weak Static Stability No Blocking→ Linear Theory Applied to Oregon Climate



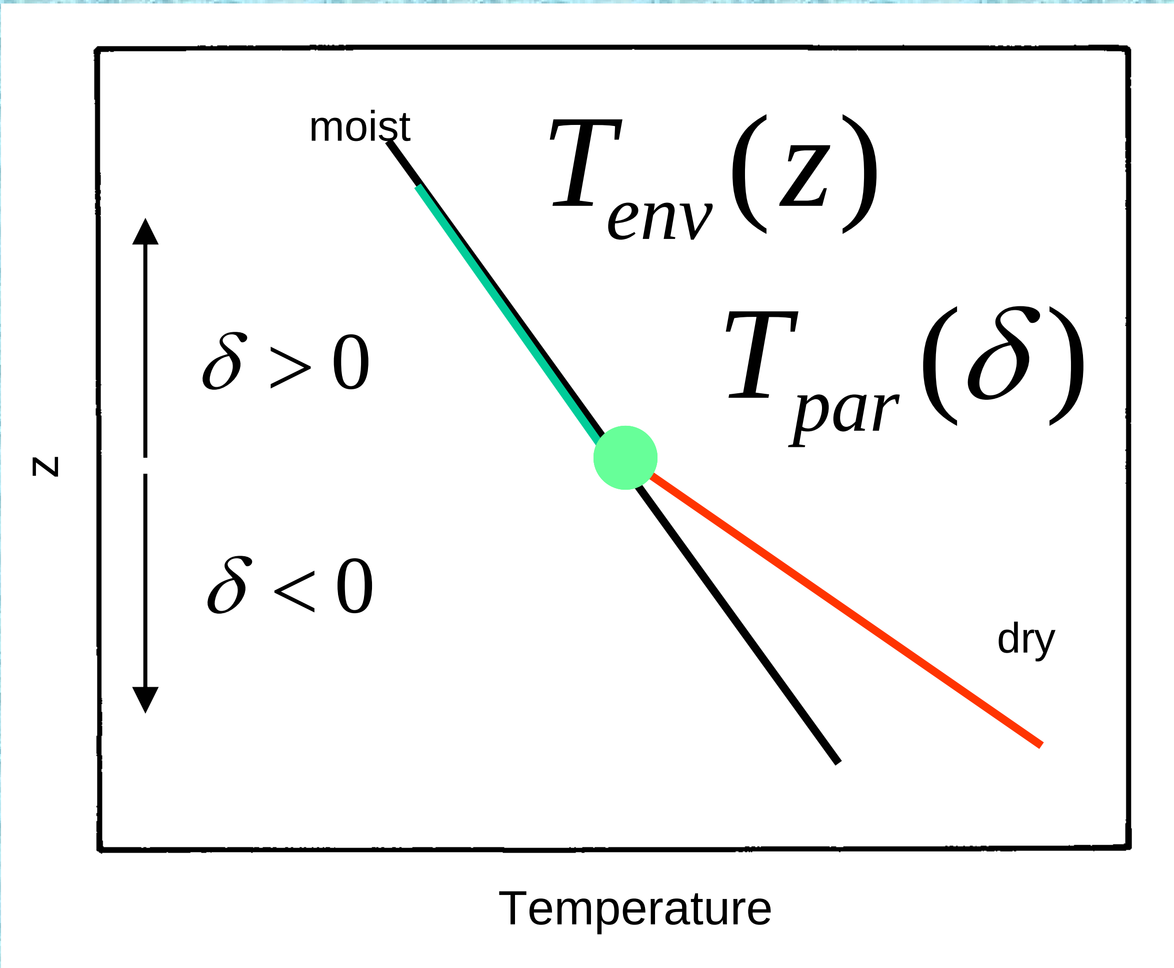
Topography (Oregon)

Obs

Linear Theory

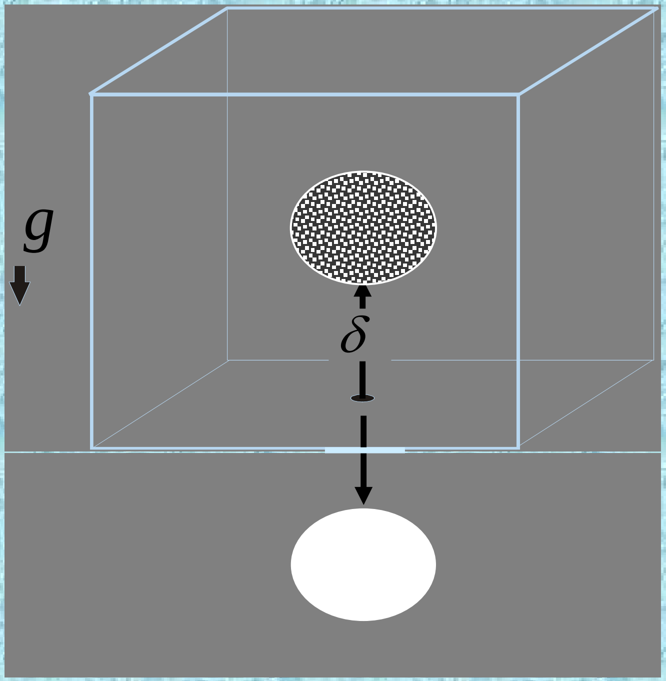
Smith, Bonneau and Barstaad (*J. Atmos. Sci.*, 2004)

Air Parcel Behavior with Phase Change



Latent Heat Release can Produce Asymmetric Effects

→ Fundamental Nonlinearity



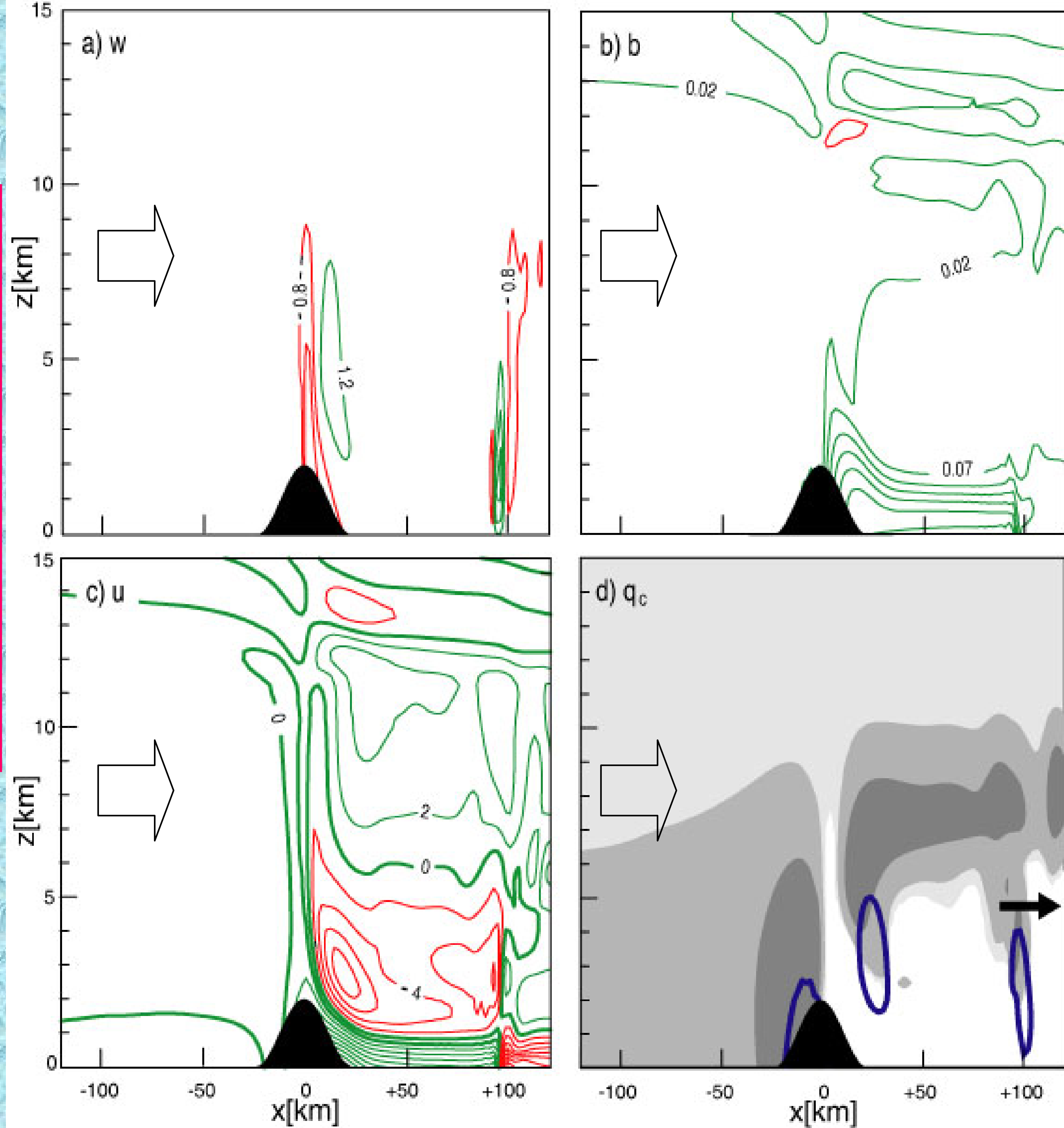
Upward Displacement: Parcel Remains Saturated

Downward Displacement: Parcel May Desaturate

$$B = -N_m^2 \delta \quad if \;\; \delta > 0$$
$$B = -N_d^2 \delta \quad if \;\; \delta < 0$$

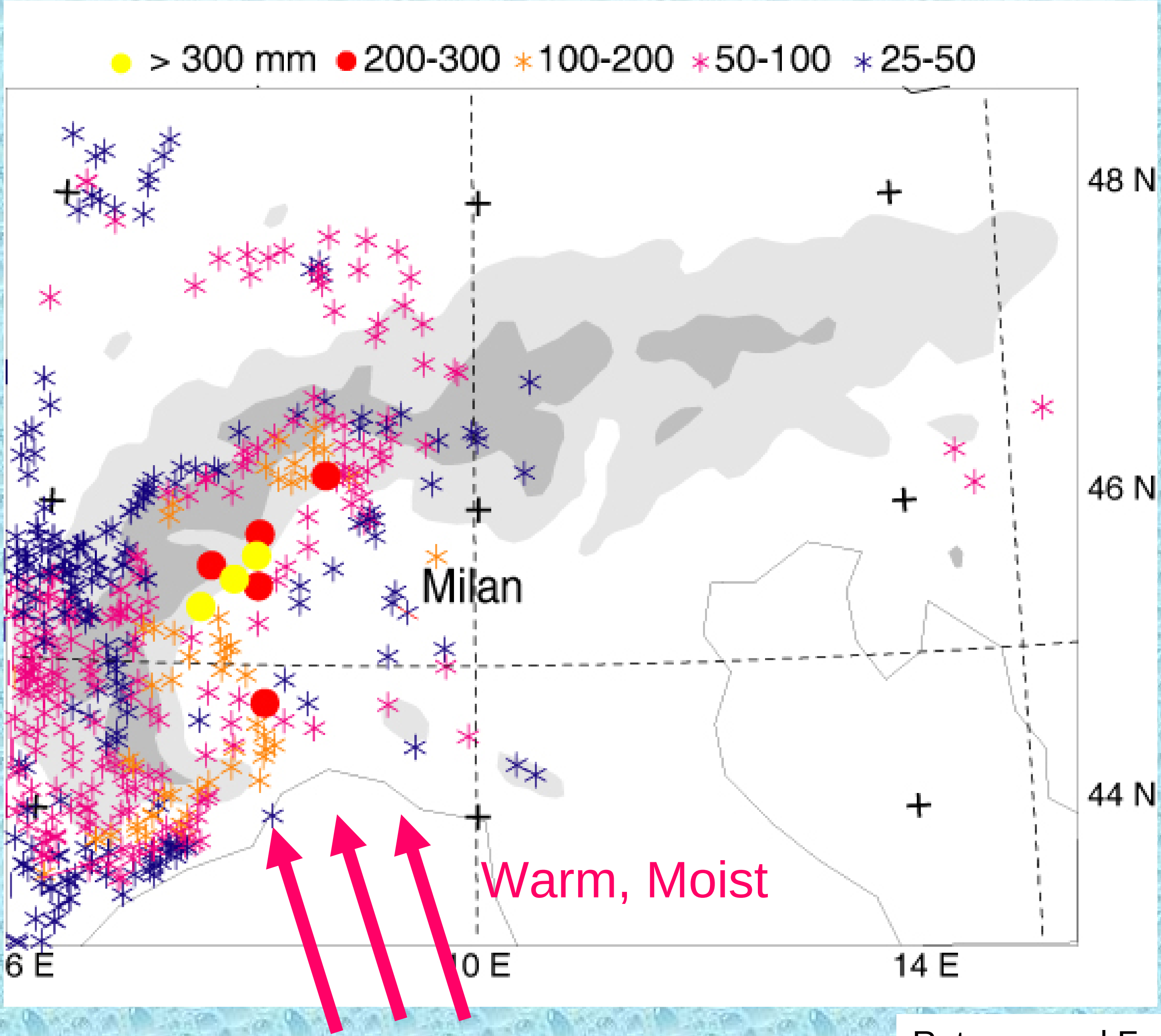
Barcilon, Jusem and Drazin (1979)

Saturated Conditions Upstream, Unsaturated Conditions Downstream/ (Foehn)Wind



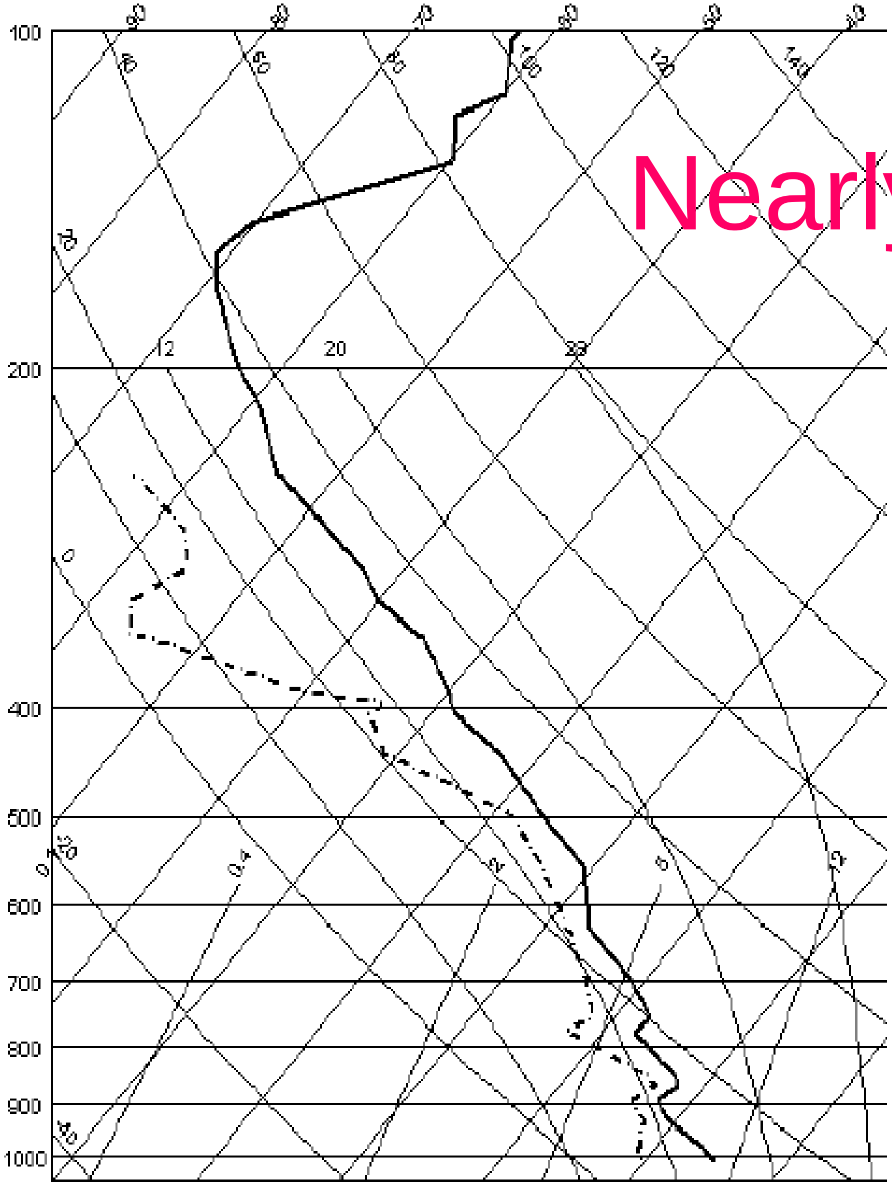
Miglietta and Rotunno (*J. Atmos. Sci.*, 2005)

Piedmont Flood November 1994 (Obs Rain 06z 5 Nov –06z 6 Nov)



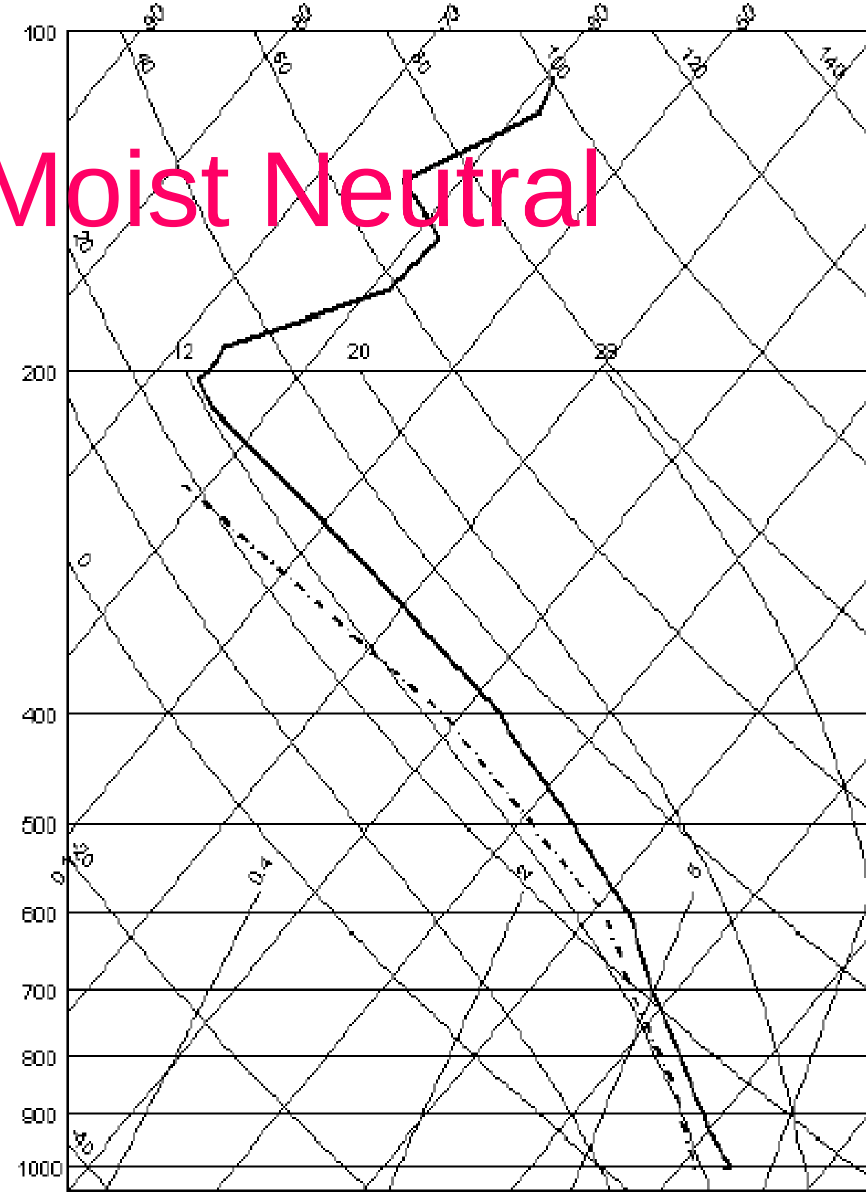
Rotunno and Ferretti (2001)

12 Z 5 Nov 1994 Milan



plotted Wed Mar 22 01:18:27 2000 using an Splus program by Ch. Haeberli IMGW

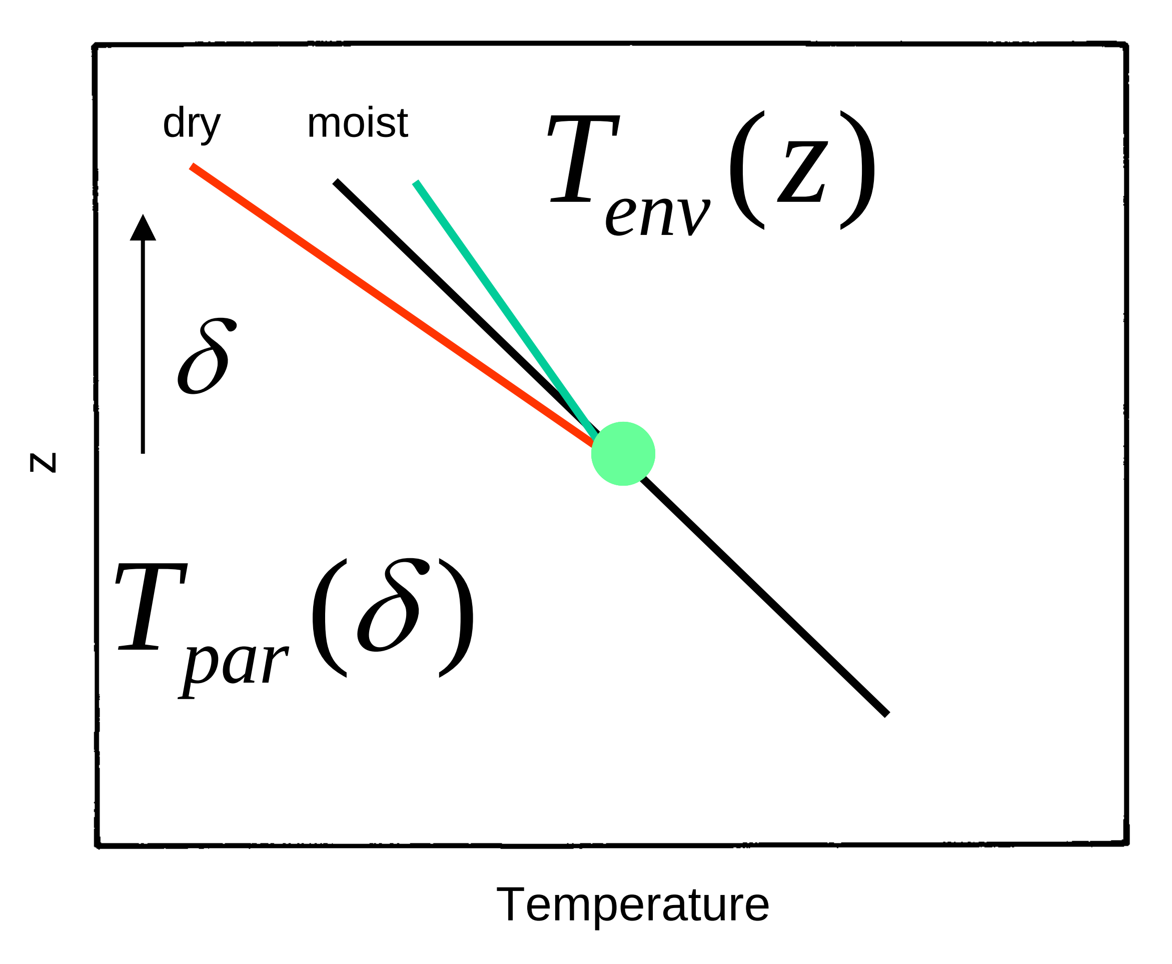
00 Z 6 Nov 1994 Milan



plotted Wed Mar 22 01:30:39 2000 using an Splus program by Ch. Haeberli IMGW

Nearly Moist Neutral

Air Parcel Behavior with Phase Change



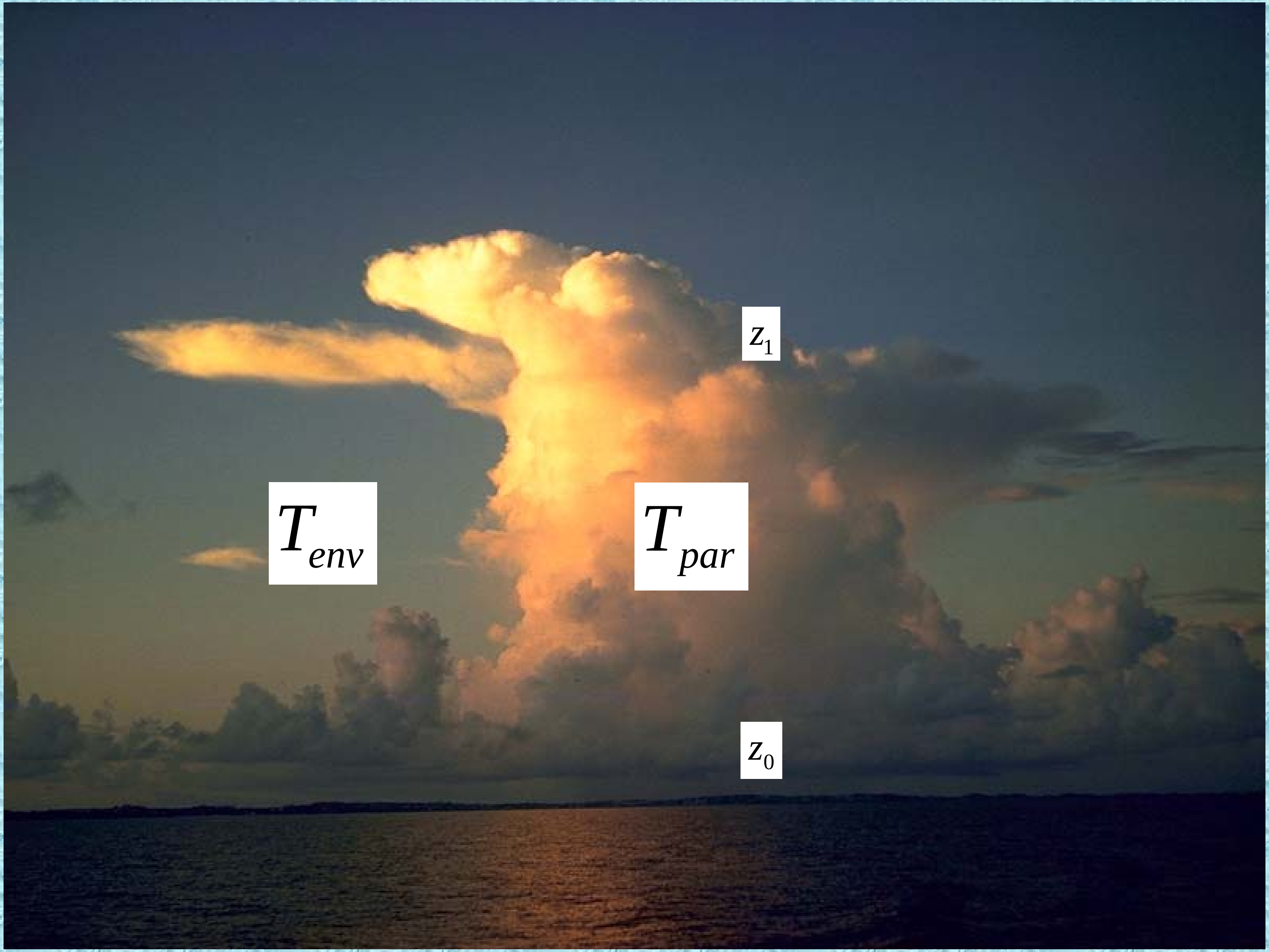
Latent Heat Release can Produce Instability

Global Measure: Convective Available Potential Energy

$$CAPE = \int_{z_0}^{z_1} B\,dz$$

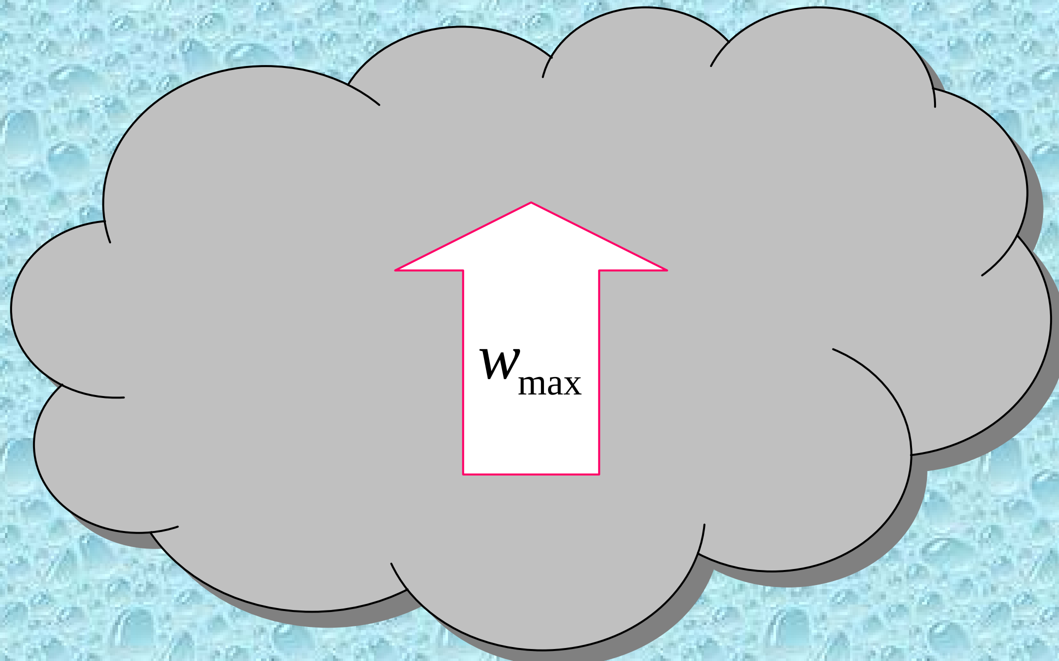
$$\int_{z_0}^{z_1} B\,dz = R_d \int_{p(z_1)}^{p(z_0)} \left(\breve{T}_{par} - \breve{T}_{env}\right) d\ln p$$

Emanuel (1994)



$$T_{par} > T_{env}$$

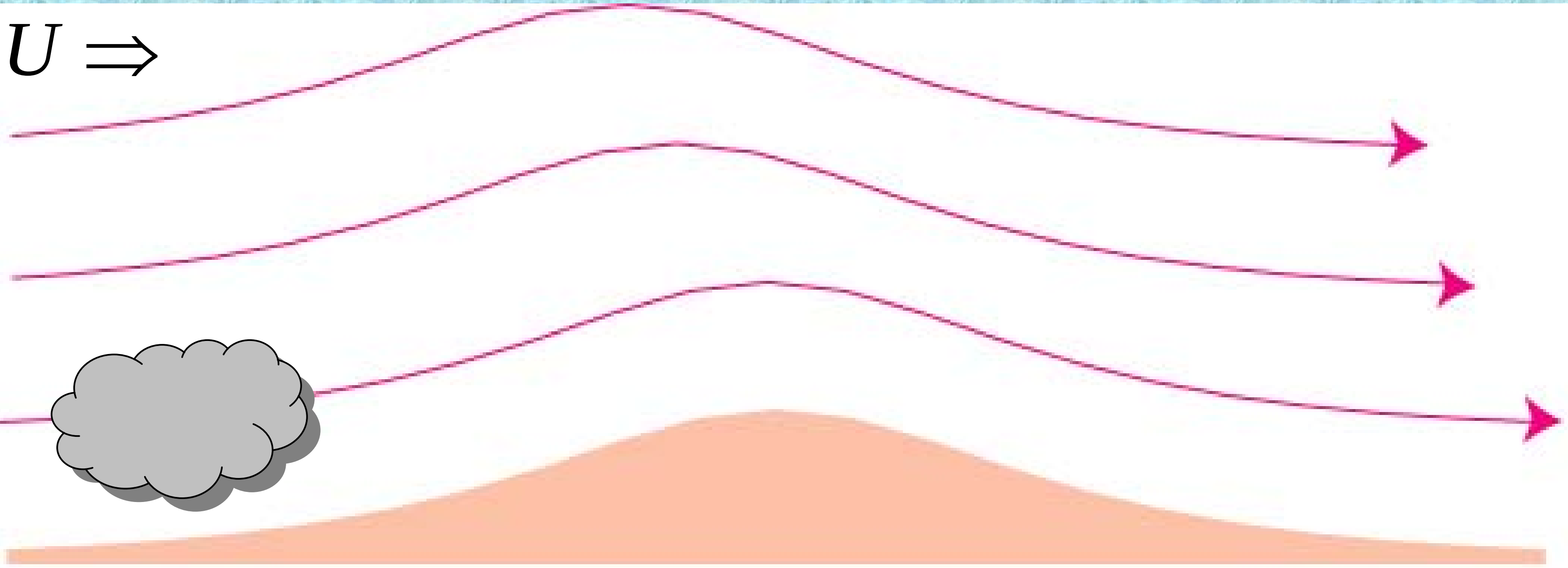
$$w_{\max} = \sqrt{2 \times CAPE} \sim 2 - 50 m/s$$



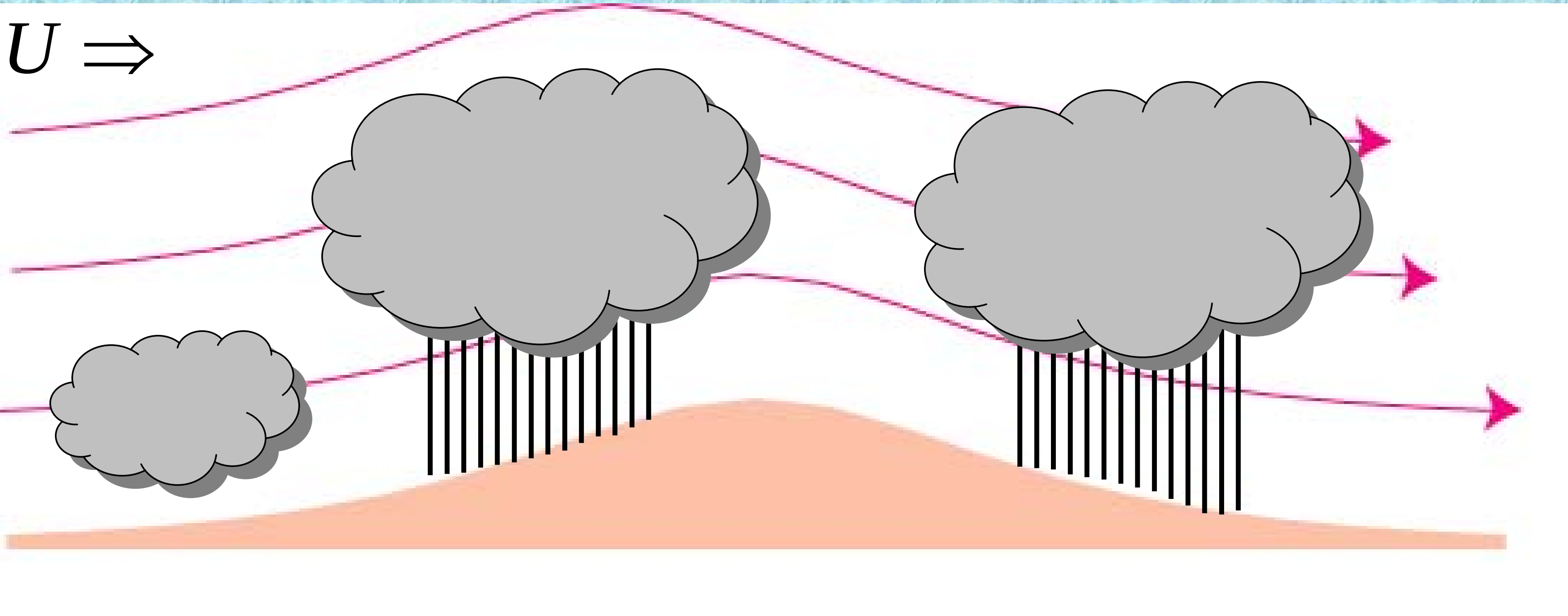
$$C(z_0) = \int_{z_0}^{\infty} -w(x,z)\frac{\partial \rho_{vs}}{\partial z} dz$$

$$C(z_0) \approx w_{\max}\rho_{vs}(z_0) = 2m/s \times \ \times .01Kg/m^3 = 72\ mm/h\ !!!$$

Orographic Effect on Moist Convection

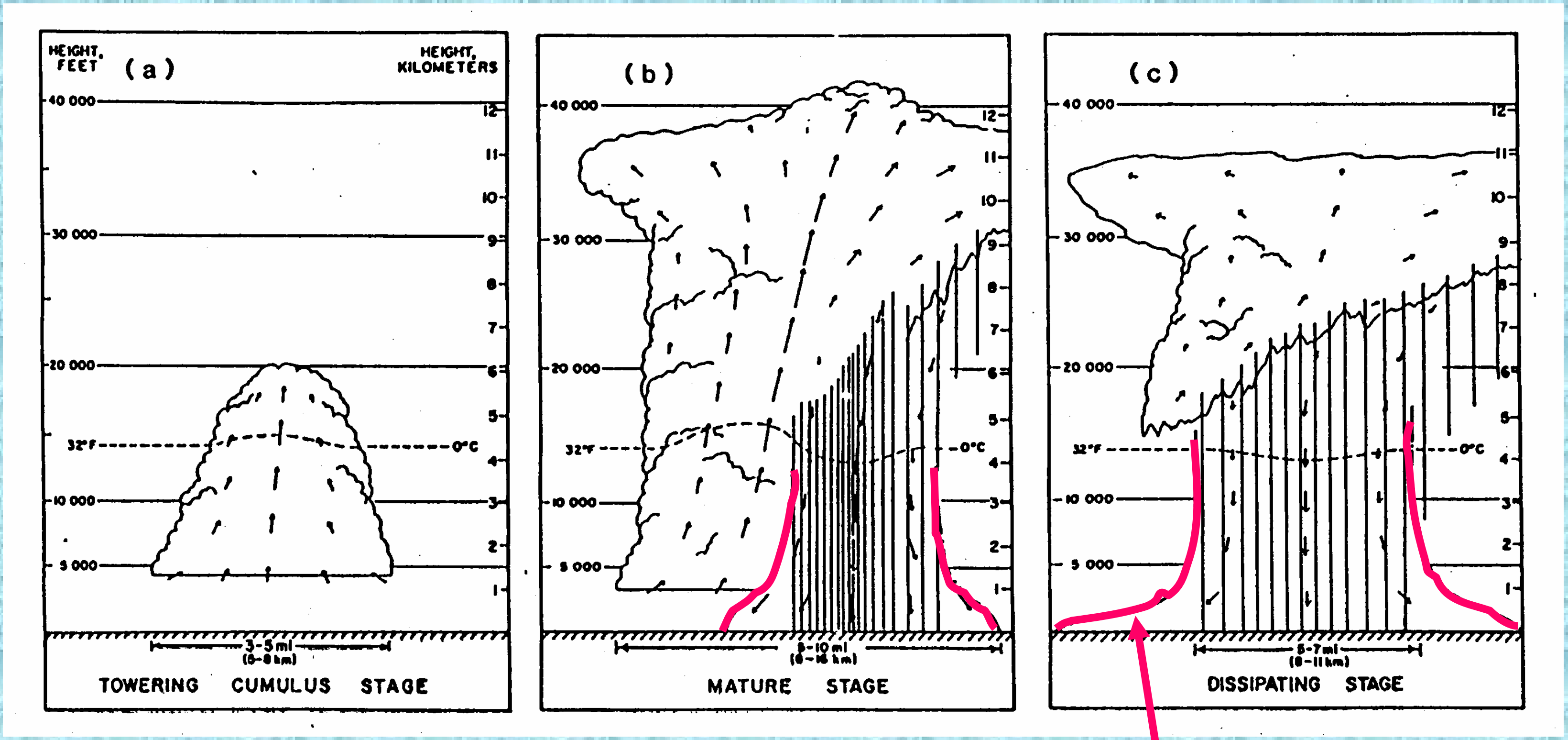


Good News:
Upslope Flow Can Provide Lift to
Overcome Threshold (E.g. Stable Layers)



Bad News:
Upslope Wind Moves Cells Downwind→ Rain Accumulation Small

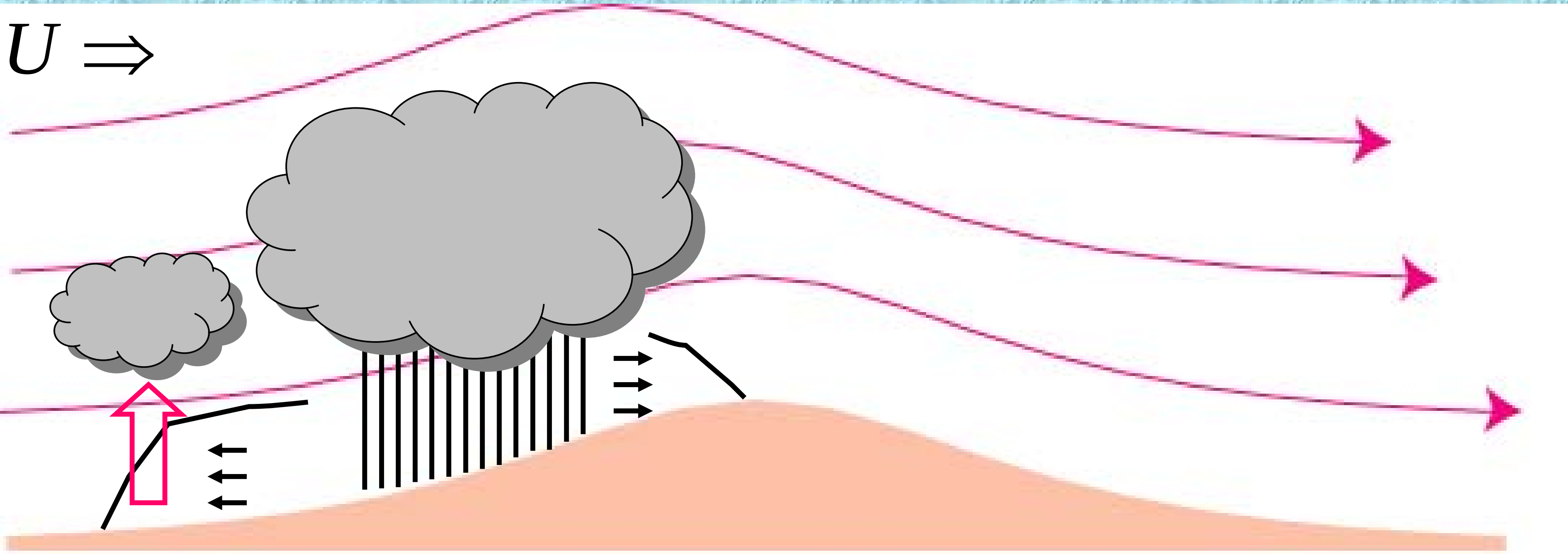
Typical Rain Cell Life Cycle



Cold Air Outflow

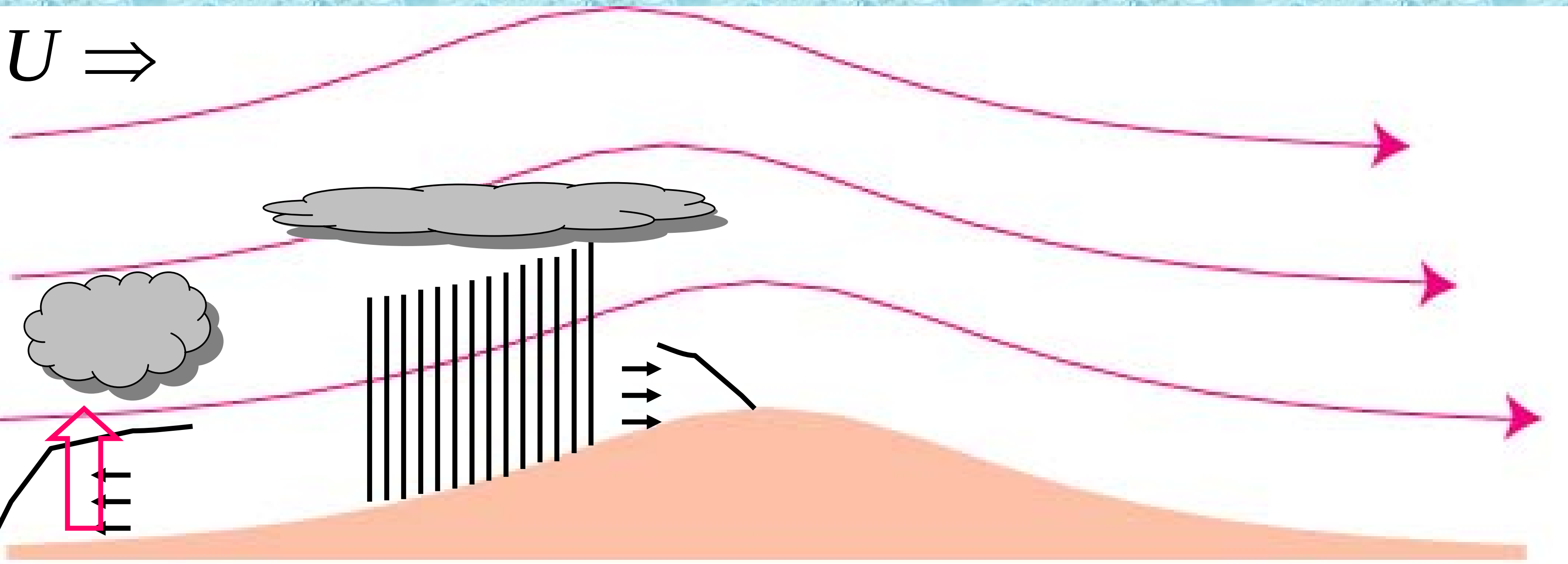
Byers and Braham (1948)

Good News: Cool Air Outflows May Initiate New Cells Upstream →



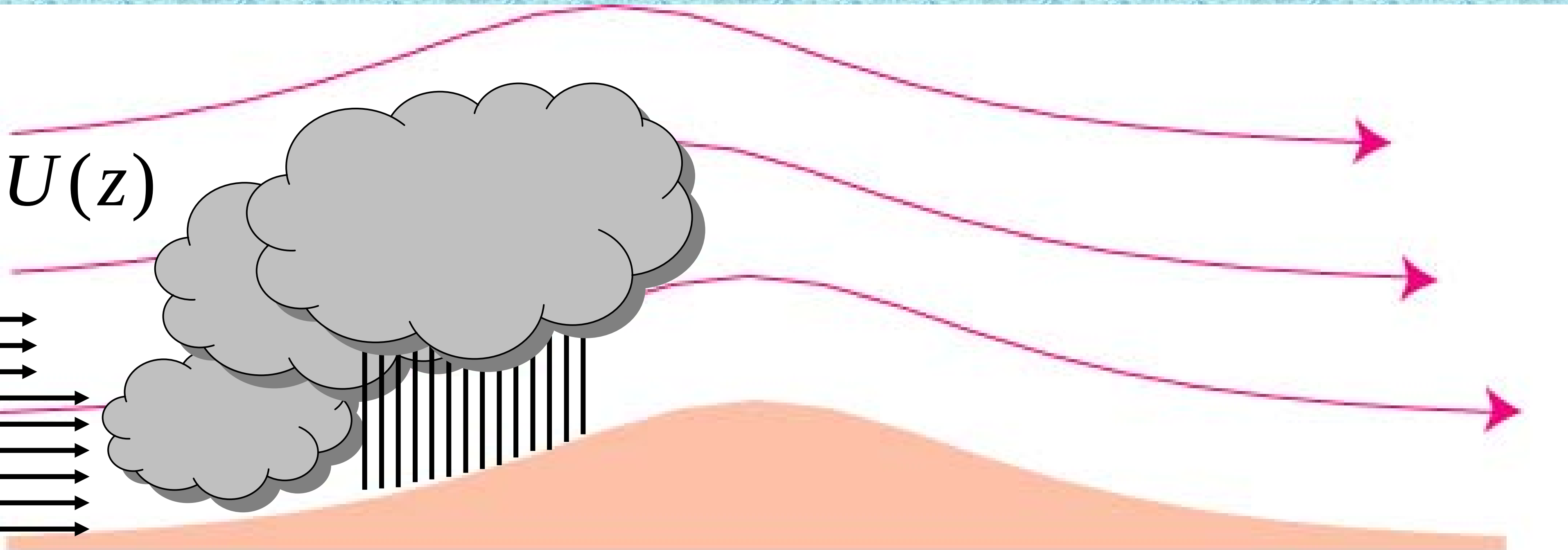
Chu and Lin (2000)

Bad News: Cool Air Outflows May Propagate Too Far Upstream

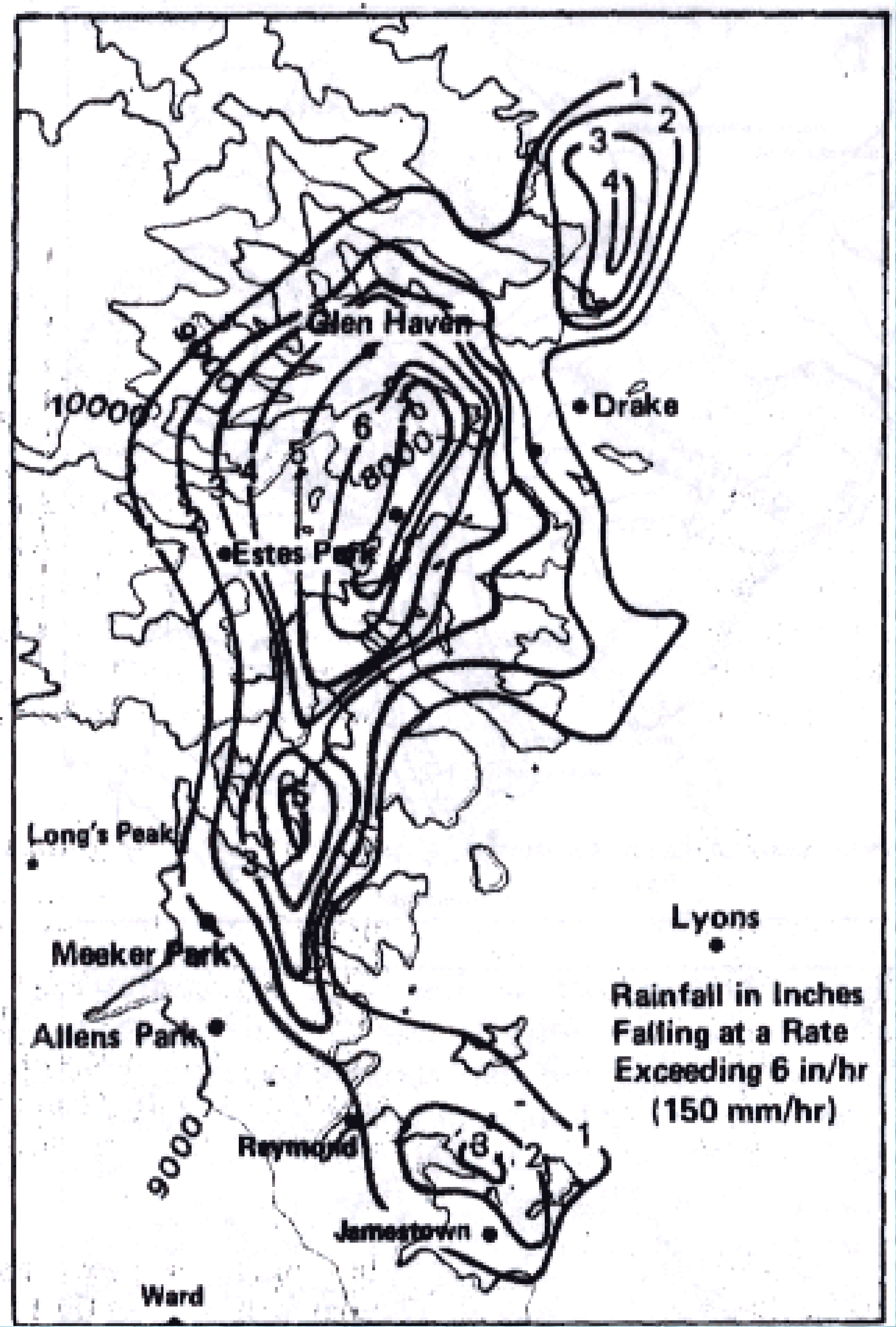


Chu and Lin (2000)

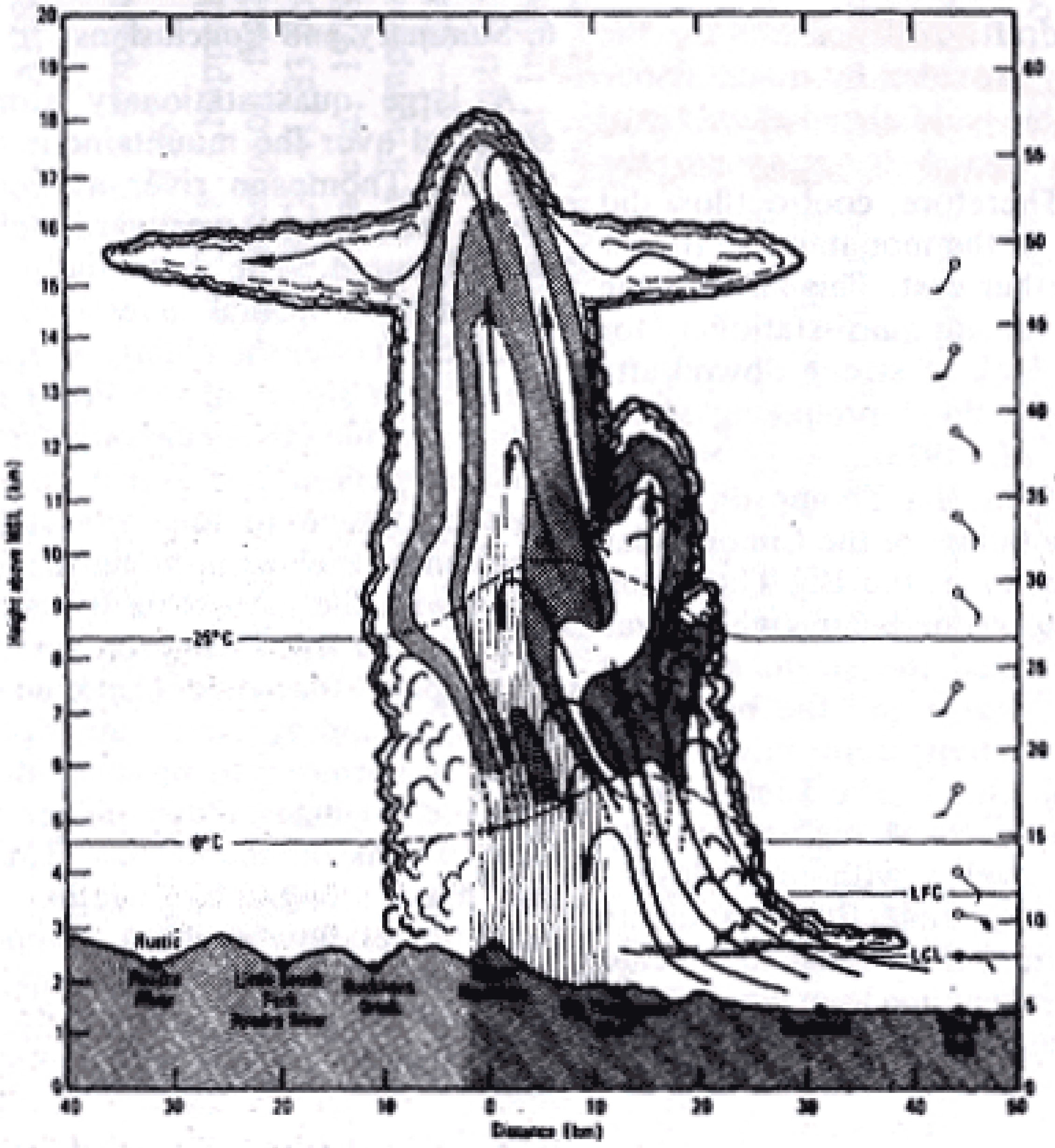
Good News:Rain Accumulation Large if Wind Varies with Height such that Cells are Stationary wrt Mountain→



Big Thompson Flood Colorado, 1976



Caracena et al. (1979)



Caracena et al. (1979)

Summary

- Dynamics of orographic air flow strongly coupled to latent heating
- Stable Case: Latent heating renders flow less stable making possible flow over tall mountains condensing large amounts of water vapor. Microphysics present major uncertainties, however.
- Unstable Case: Convective cells may produce large amounts of condensed water, but motion of cells wrt to mountain makes detailed prediction difficult.