A New Approach for Estimating Entrainment Rate in Cumulus Clouds

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Many Thanks to Drs. Hermann Gerber, Pavel Romashkin and Allen Schanot.

Motivation

- Entrainment of dry air into clouds is essential to warm-rain initiation and radar retrieval of liquid water content.
- Entrainment rate is critical for convection and cloud microphysics.
- But the topic is poorly understood and the entrainment rate values reported in the literature suffer from a wide range of uncertainties.

Formulations of the New Approach

$$\lambda \equiv \frac{1}{m}\frac{dm}{dz}$$

λ: entrainment rate

***m*: mass of a cloud parcel**

***z*: height**

$$\int_{z_0}^{z} \lambda dz = \int_{m(z_0)}^{m(z)} \frac{dm}{m} = \ln \frac{m(z)}{m(z_0)}$$

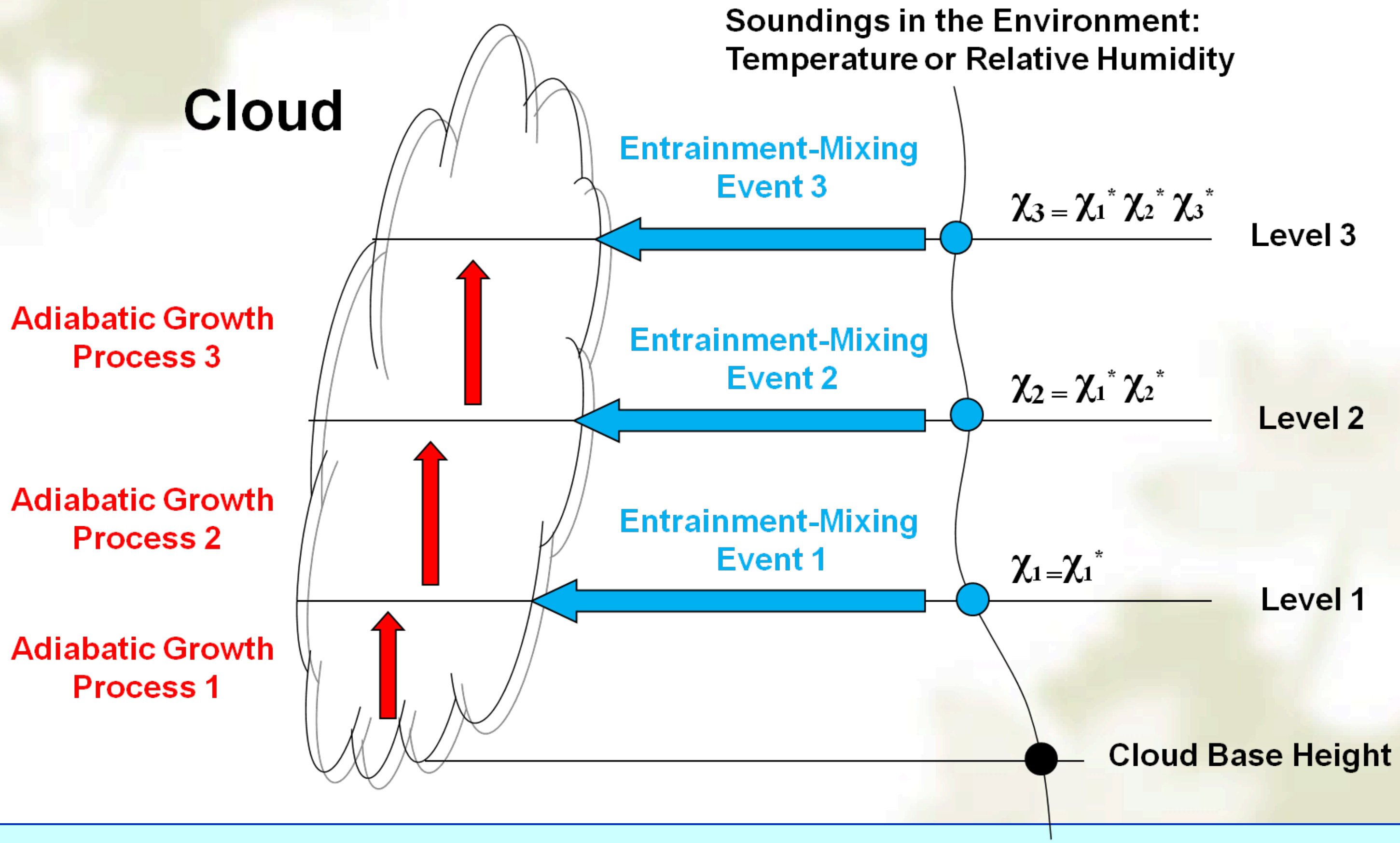
z_0: cloud base height

$$\lambda = \frac{\ln \frac{m(z)}{m(z_0)}}{z - z_0} = \frac{-\ln \chi}{h}$$

$h = z - z_0$

$\chi = m(z_0)/m(z)$: mixing fraction of adiabatic cloud

Estimation of Mixing Fraction χ(1)



Quantities needed: cloud base height, temperature at cloud base, temperature and water vapor content in environment, and liquid water content at all levels in cloud.

Estimation of Mixing Fraction χ (2)

For every entrainment and isobaric mixing process:

(1) Total water (q_t) conservation:

$$q_t = q_{t\_cloud}\chi^* + q_{t\_environment}(1-\chi^*)$$

(2) Liquid water potential temperature (θ_l) conservation:

$$\theta_l = \theta_{l\_cloud}\chi^* + \theta_{l\_environment}(1-\chi^*)$$

$$\chi_n = \chi_1^*\chi_2^*\chi_3^*\cdots\chi_n^*$$

Validation with Aircraft Observations (1)

A non-drizzling cumulus case in RICO (Rain in Cumulus over the Ocean)

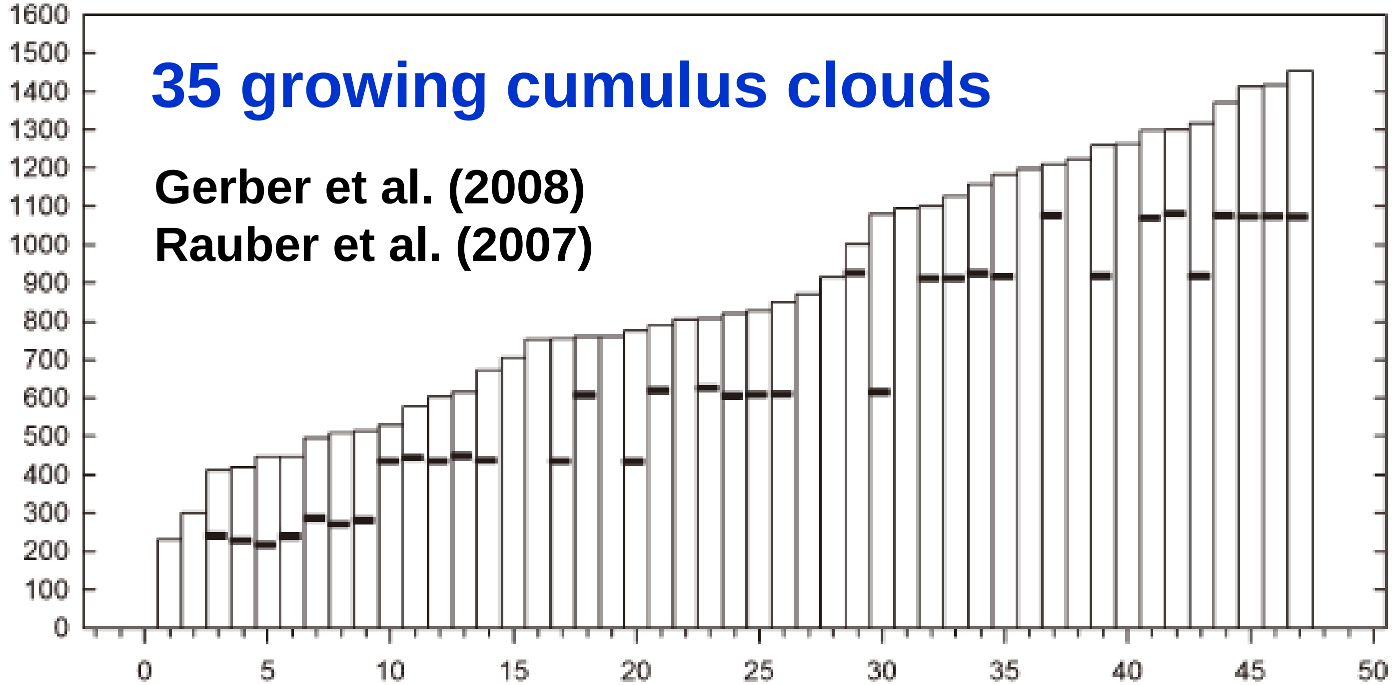
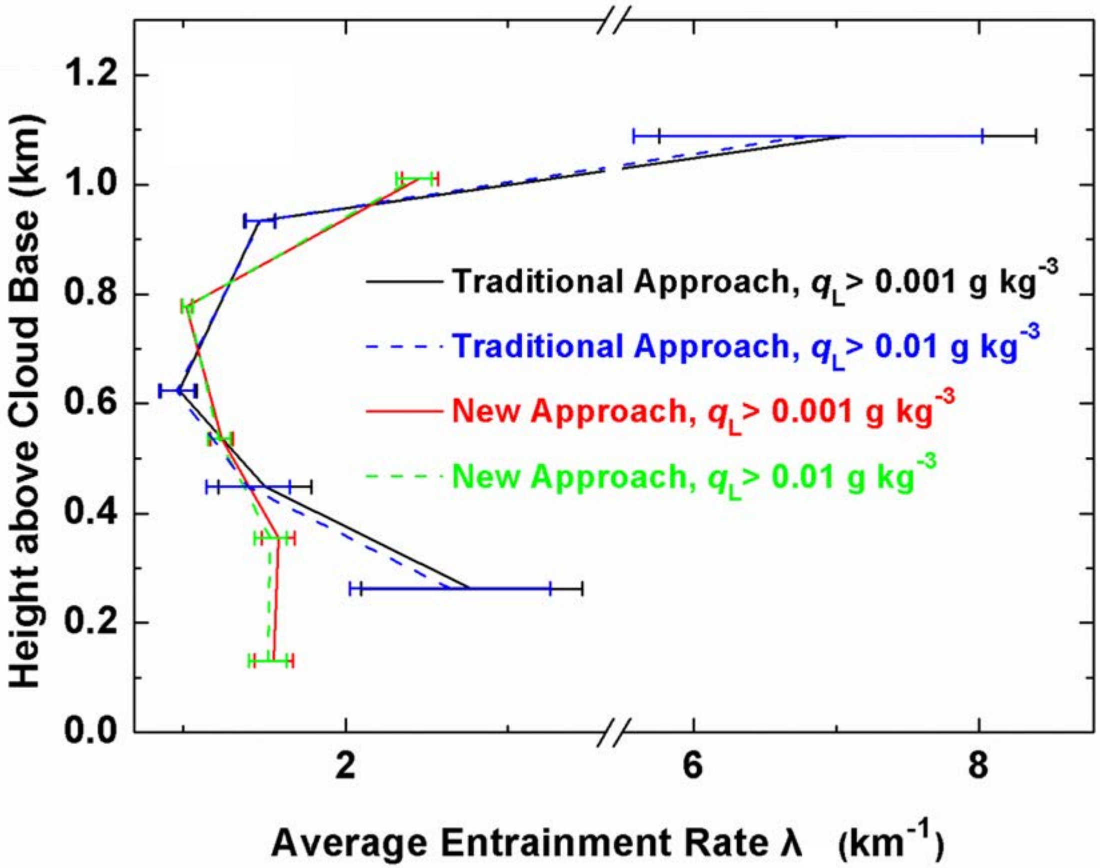


Fig. 2. Height z_t of cloud top measured from cloud base z_0 for 47 individual trade-wind Cu on flight RF12. Dark horizontal bars indicate the 35 Cu chosen by conditional sampling for this study (see text), and indicate the penetration height of the aircraft flown at an average distance of about 250-m below cloud top at 5 levels.

Validation with Aircraft Observations (2)

A non-drizzling cumulus in RICO (Rain in Cumulus over the Ocean) (Gerber et al., 2008)



The new approach has smaller uncertainties.

Traditional Approach (Betts, 1975):

$$\lambda = \frac{\partial \phi_c / \partial z}{\phi_e - \phi_c}$$

λ Entrainment rate

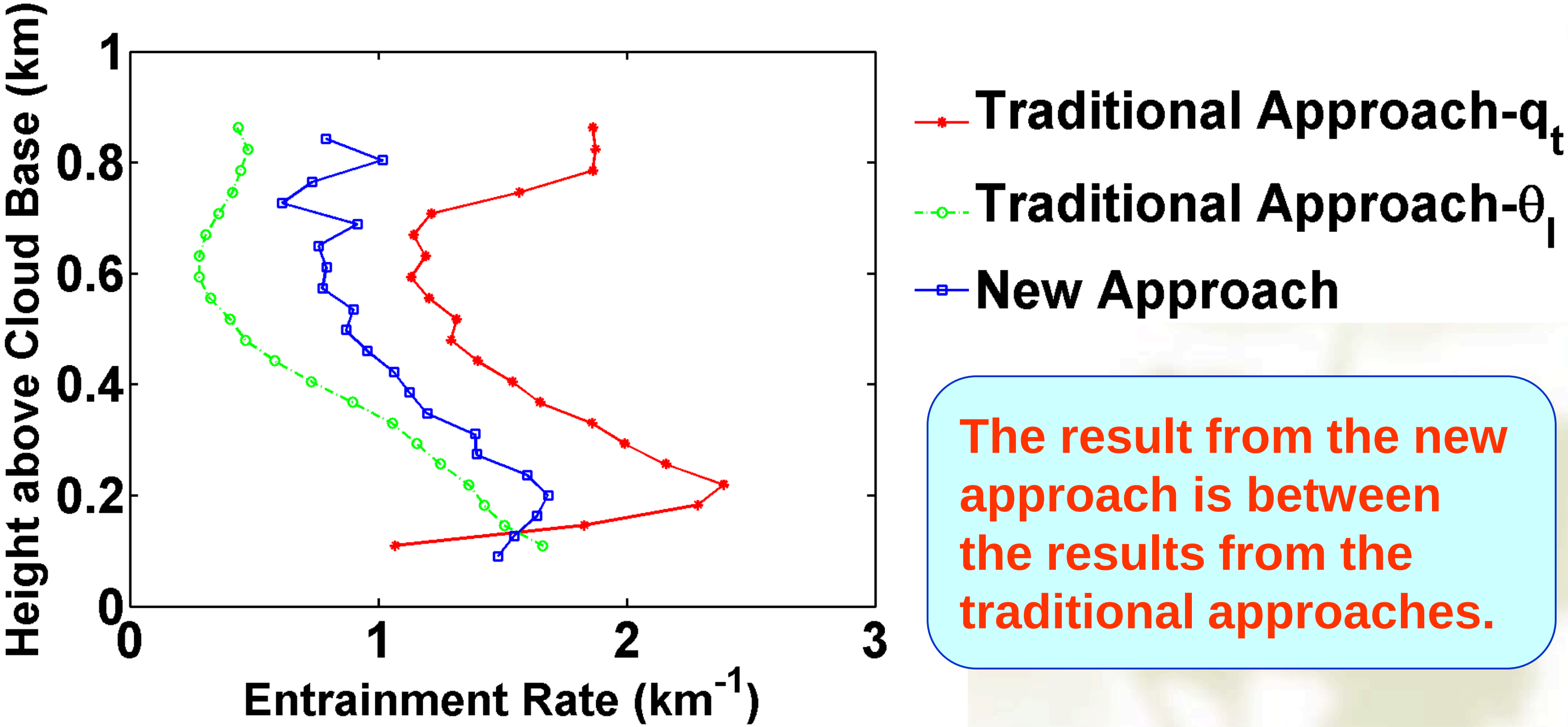
ϕ_c Value of a conserved property in cloud

ϕ_e Value of a conserved property in environment

z Height

Validation with LES Results

A benchmark case over the SGP site simulated by an LES model, WRF-FASTER.



The result from the new approach is between the results from the traditional approaches.

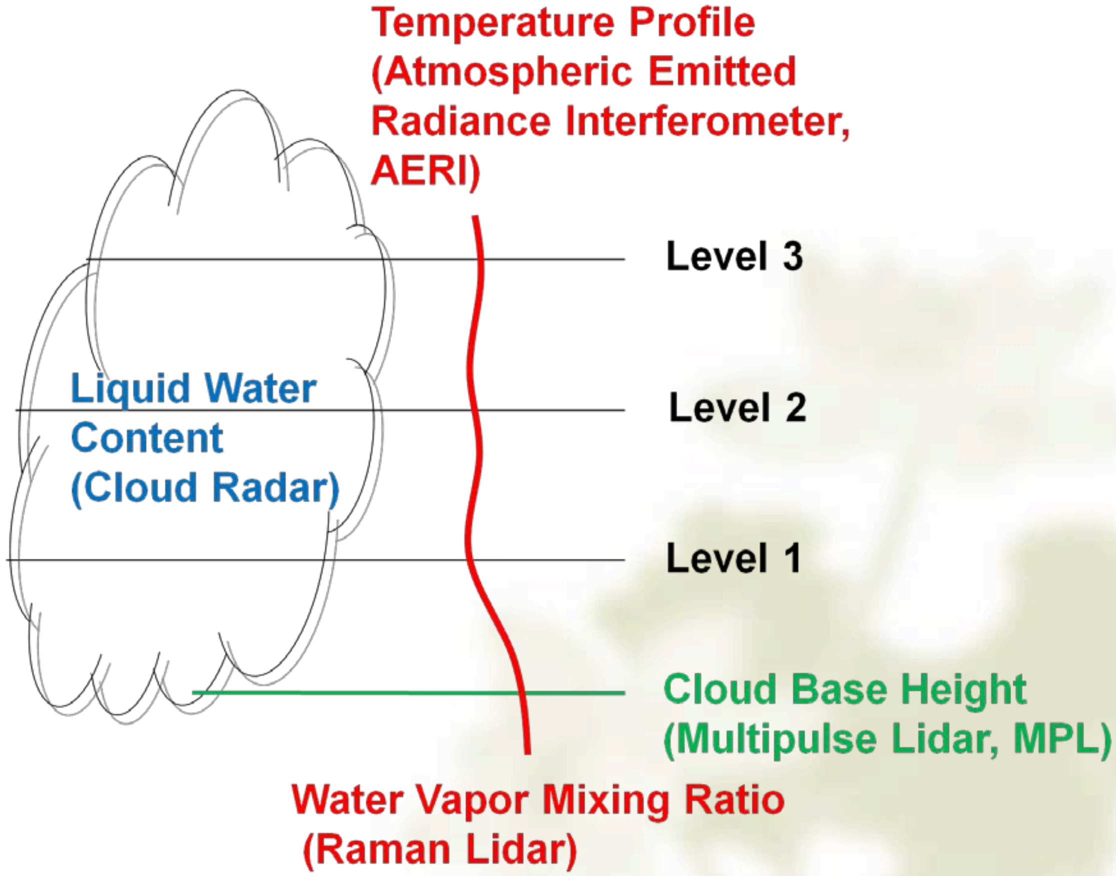
Advantages of the New Approach (1)

- Elimination of the need for in-cloud measurements of temperature and water vapor content, which are usually difficult and problematic;

- The potential to directly connect the microphysical effects of entrainment mixing and the estimation of entrainment rate.

Advantages of the New Approach (2)

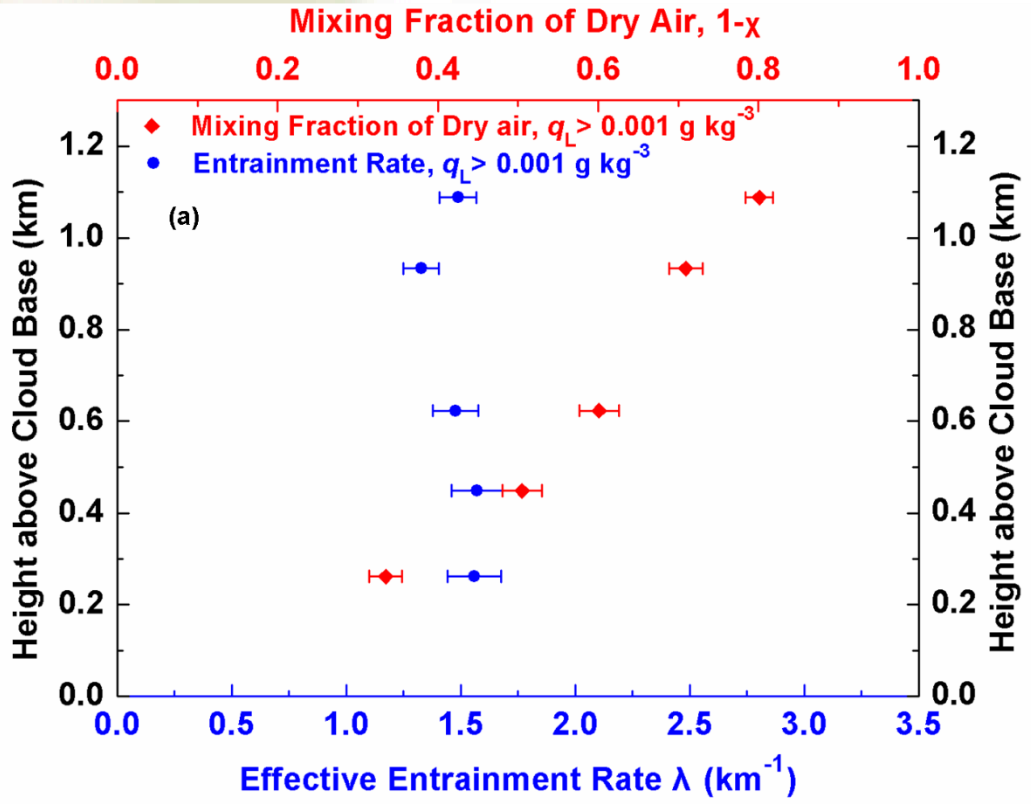
The potential for developing a remote sensing technique to infer entrainment rate profiles.



Thanks!

Backup Slides

Adjustment of Entrainment Rate



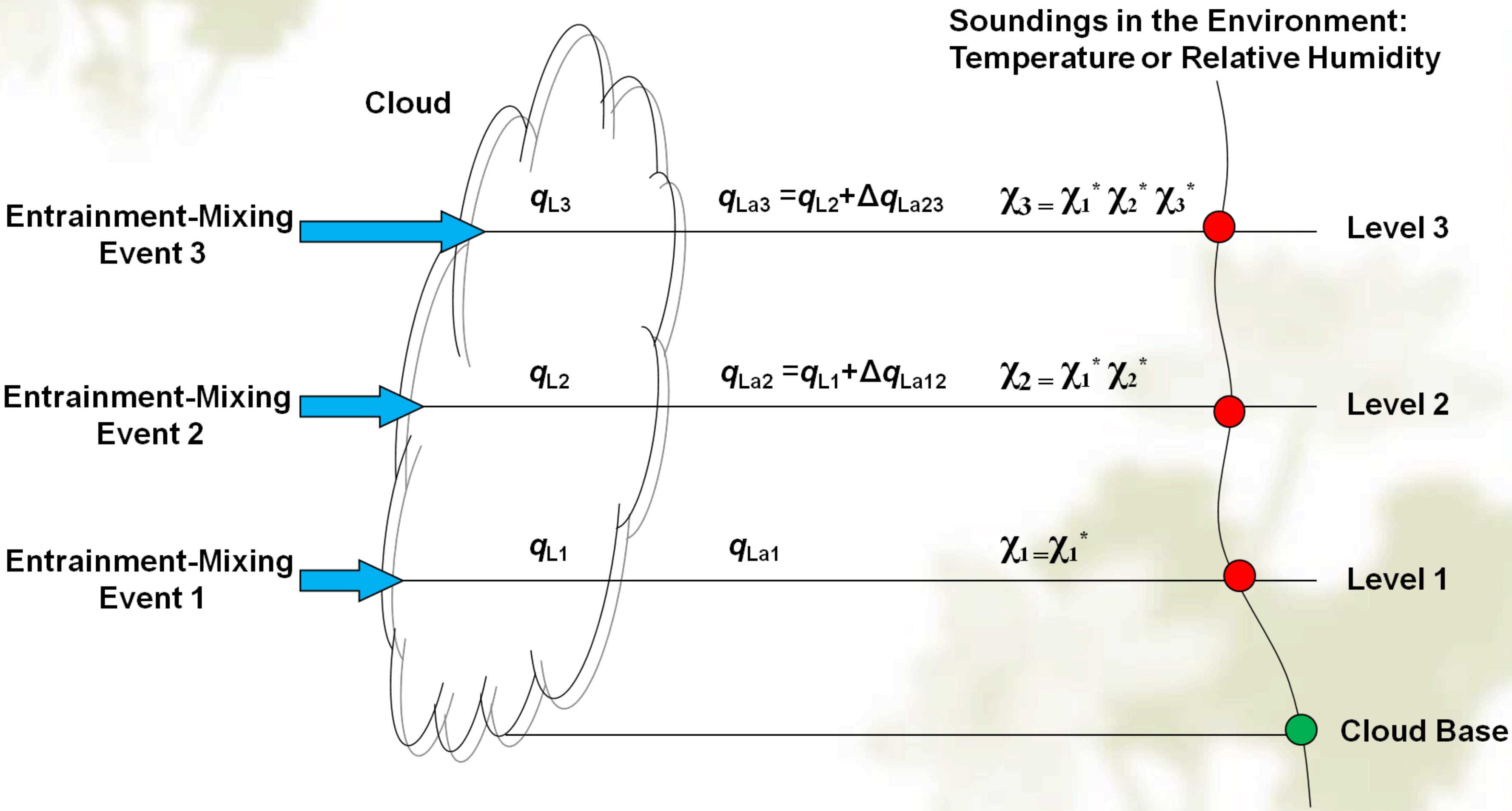
$$\lambda_{\mathrm{pj}} = \frac{\lambda_{\mathrm{j}} h_{\mathrm{j}} - \lambda_{\mathrm{j-1}} h_{\mathrm{j-1}}}{h_{\mathrm{j}} - h_{\mathrm{j-1}}}$$

j =2, 3,…, n

$$\lambda_{\mathrm{pj}} = \lambda_{\mathrm{j}}$$

j = 1

Estimation of Mixing fraction χ(1)



Estimation of Mixing fraction χ (2)

For every entrainment process:

(1) Total water conservation:

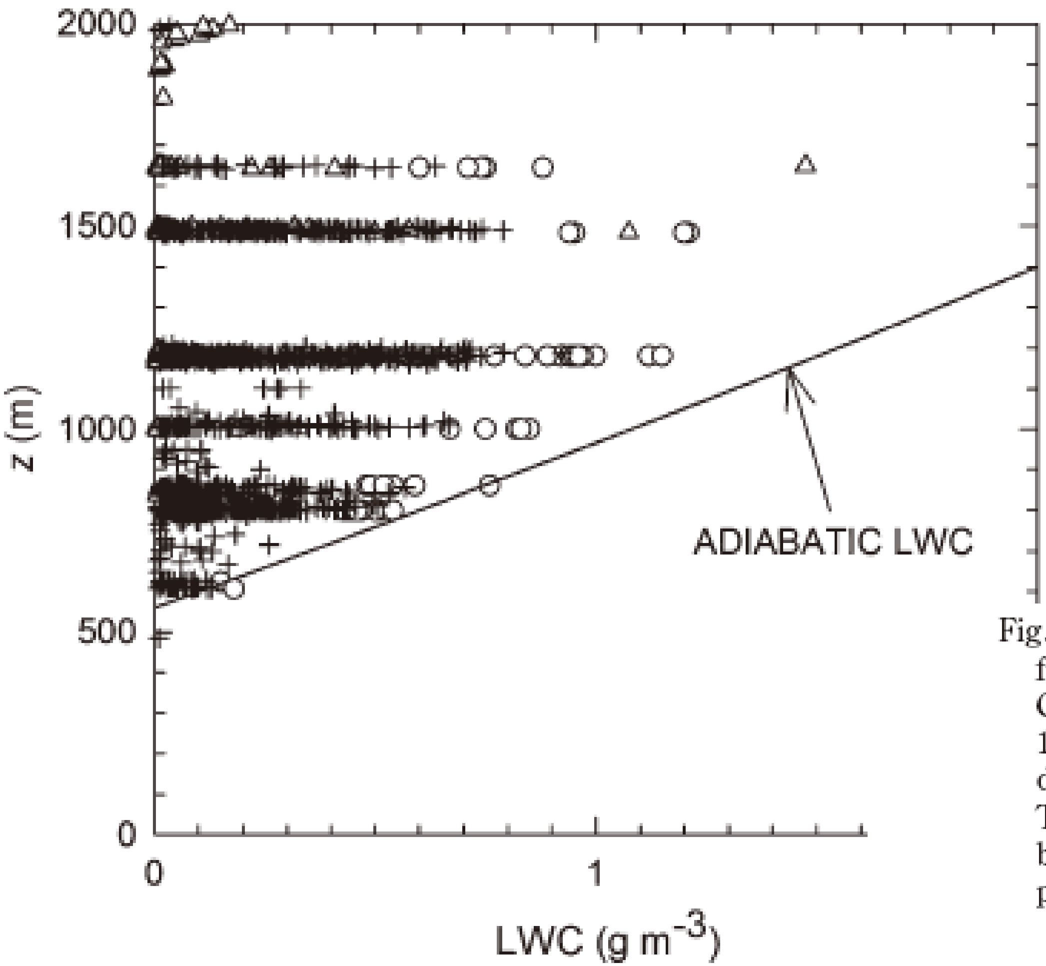
$$q_t = q_{t\_cloud}\chi^* + q_{t\_environment}(1-\chi^*)$$

(2) Liquid water potential temperature conservation:

$$\theta_l = \theta_{l\_cloud}\chi^* + \theta_{l\_environment}(1-\chi^*)$$

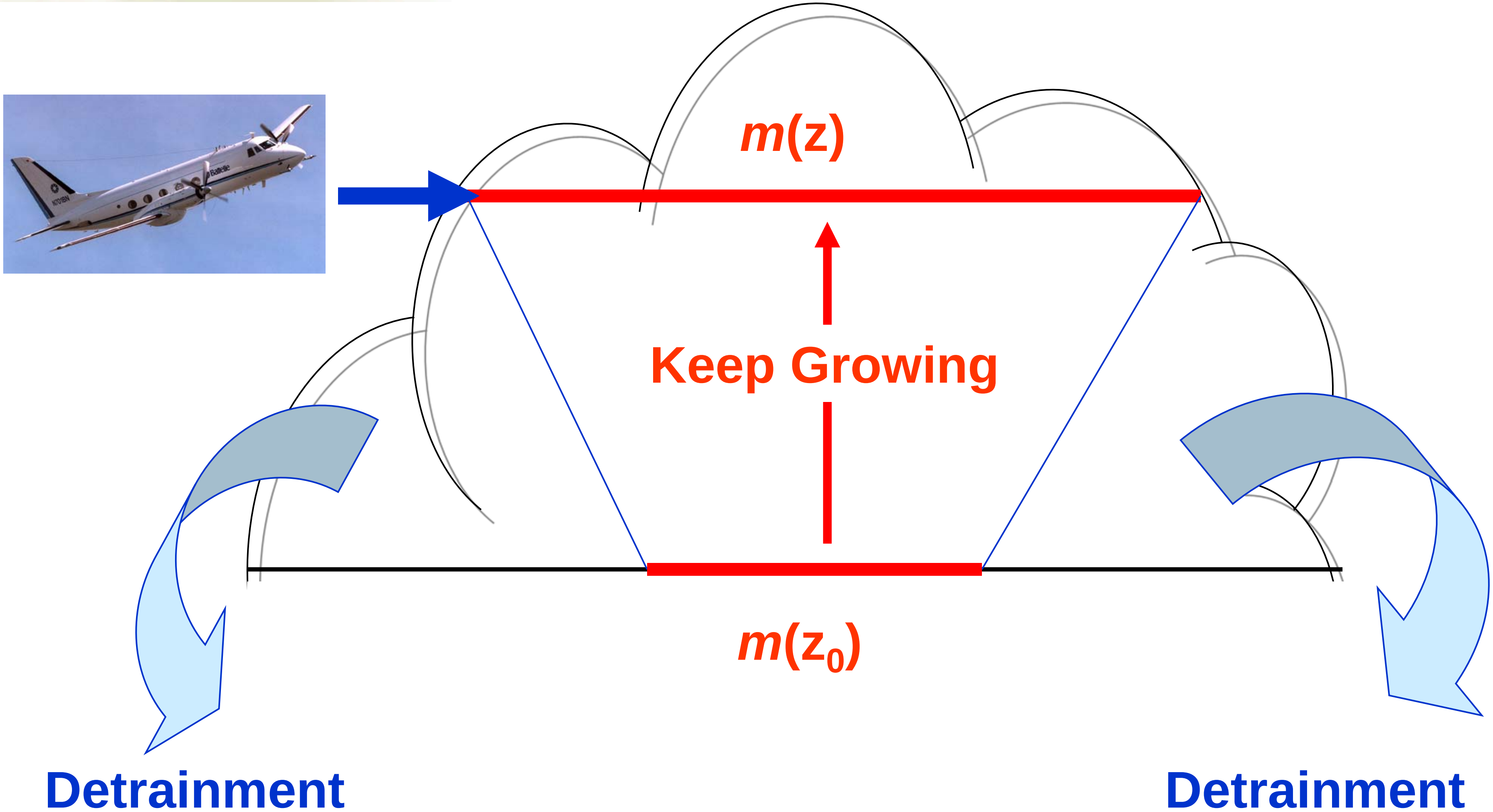
$$\chi_n = \chi_1{}^* \chi_2{}^* \chi_3{}^* \cdots \chi_n{}^*$$

Cloud Base Estimation



Gerber et al. (2008)

Fig. 1. Liquid water content LWC as a function of height z in RICO trade-wind Cu on C-130 flight RF12. Crosses are 1-hz PVM data, circles are 1000-hz PVM data, and triangles are 1-hz 2D-C data. The curve indicates the expected adiabatic LWC profile given cloud-base temperature and pressure.



m(z)
Keep Growing
m(z0)
Detrainment
Detrainment