Mesoscale convective systems and convection parameterisations in GCMs

Figure: Tropical thunderstorm

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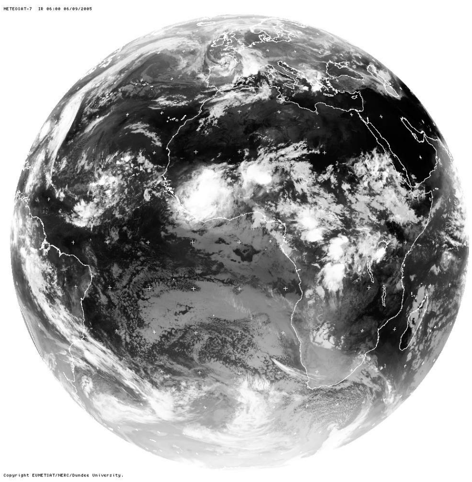
Motivation



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Recap

Summary of the evolution of thunderstorms (from a convective cell to a line of thunderstorms/multicell thunderstorm). Involved processes:

- Updraft in convective cell
- Storm splitting
- Enhancement/suppression of splitted cells
- Strom propagation
- Downbursts/gust front
- Triggering new cells from gust front

Gust front

Photo: A. Mühlbauer

Overview

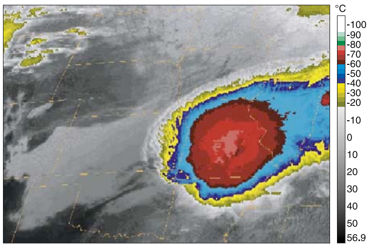


Figure 1. Infrared satellite image of a mesoscale convective system over Missouri. Courtesy of J. Moore, St. Louis University, St. Louis, Missouri.

Houze, 2004

Definition: A Mesoscale Convective System (MCS) is a cloud system that occurs in connection with an ensemble of thunderstorms and produces a contiguous precipitation area of ∼100 km or more in horizontal scale in at least one direction

Fundamental elements

- convective region (intense vertically extending cores)
- stratiform region (uniform texture of lighter precipitation)

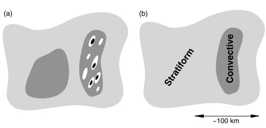


Figure 2. (a) Idealization of a horizontal map of radar reflectivity (b) divided into convective and stratiform regions. From *Houze* [1997].

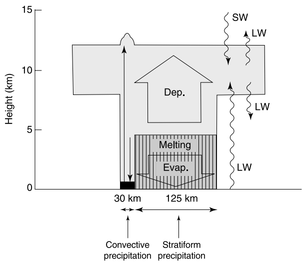
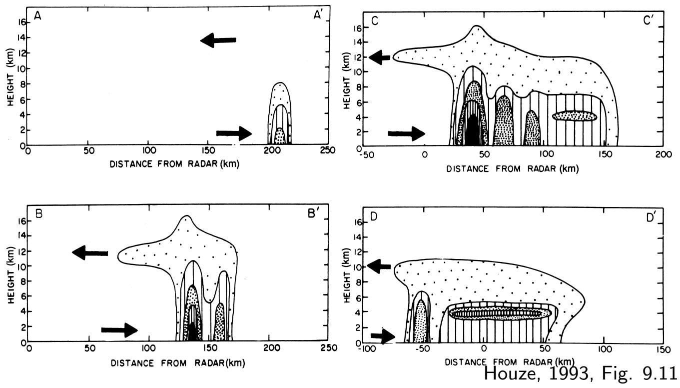


Figure 3. Schematic of a tropical mesoscale convective system in its mature stage. LW and SW indicate long- and short-wave radiation, respectively. Light shading indicates cloud. Vertical lines with medium shading indicate stratiform precipitation. Black indicates convective precipitation. Straight, solid arrows indicate convective updrafts and downdrafts. Wide, open arrows indicate mesoscale ascent and subsidence in the stratiform region, where vapor deposition (Dep.) and evaporation (Evap.) occur. Adapted from *Houze* [1982], courtesy of the Meteorological Society of Japan.

Houze, 2004

Life cycle – overview



Houze, 1993, Fig. 9.11

Layer lifting

Classical view: Parcel lifting

Air with high equivalent potential temperature θ_e is accelerated after reaching the level of free convection (entrainment/ detrainment, "lucky parcels", etc.)

In mature MCS a deep slantwise ascending layer can be found, this leads to "layer lifting"

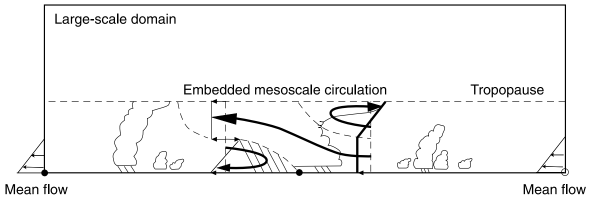


Figure 6. Schematic diagram showing the airflow relative to a two-dimensional, steady state mesoscale convective system in a large-scale environment of given wind shear. The environmental air entering the updraft is potentially unstable, and there is a pressure decrease across the system from right to left at middle levels. The streamlines are those required by conservation of mass, momentum, entropy, and vorticity. Adapted from *Moncrieff* [1992].

Houze, 2004

Cells embedded within the ascending layer

Particle fountains:

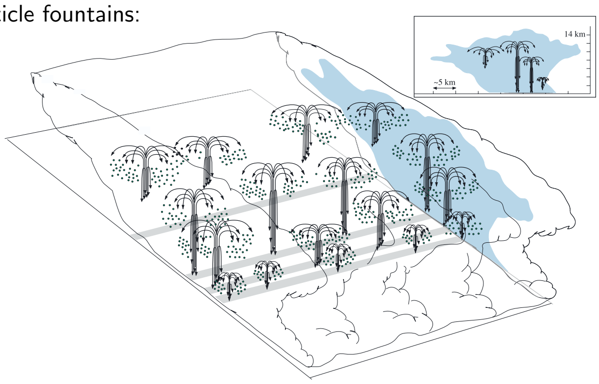


Figure 15. Conceptual model of an ensemble of particle fountains in a multicellular MCS. Shaded area represents radar reflectivity along a cross section perpendicular to the convective region. Cloud boundary is indicated by the scalloped outline. Inset shows approximate scales and arrangement of the largest particle fountains relative to the radar echo. From *Yuter and Houze* [1995b].

Houze, 2004

Cells embedded within the ascending layer

The layer of front–to–rear ascent contains flow disturbances, leading to a sequence of precipitation cells (cumulus, mature, dissipating)

Cells developing from the ascending layer act as "particle fountains", distributing precipitation over the whole MCS

The cells are triggered by the "nose" of the cold pool (i.e. outflow of the convective cells) and then propagate rearwards as gravity waves

→ deep inflow layer must be stabilised after its ascent

Mid level vortices

The ascending layer maintain a "heat" source inside the MSC

Vertical structure of the heat source leads to vortex formation in mid levels at the base of the stratiform cloud

Mid level positive vorticity: Mesoscale Convective Vortex (MCV)

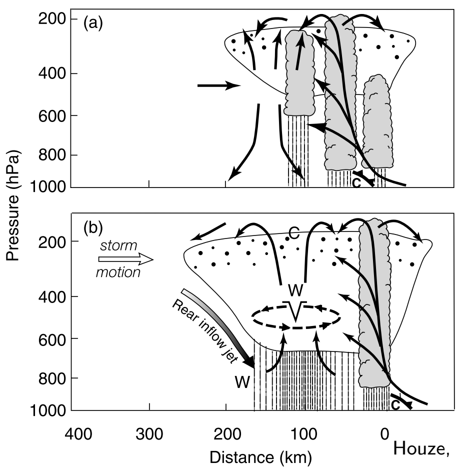
Observations: Formation of MCV favoured by

- weak flow
- wear vertical shear
- weak background vorticity
- strong gradients of humidity
- Coriolis force

⇒ Formation of a MCV occurs in the stratiform cloud region

⇒ Sometimes a MCV can trigger tropical cyclone formation

MCV – conceptual model



Houze, 2004, Fig. 21

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Convection: recap of definitions

- Lifting condensation level (LCL)
- Level of free convection (LFC)
- Level of neutral buoyancy (LNB)
- Convective inhibition (CIN)
- Convective available potential energy (CAPE)
- Entrainment/Detrainment

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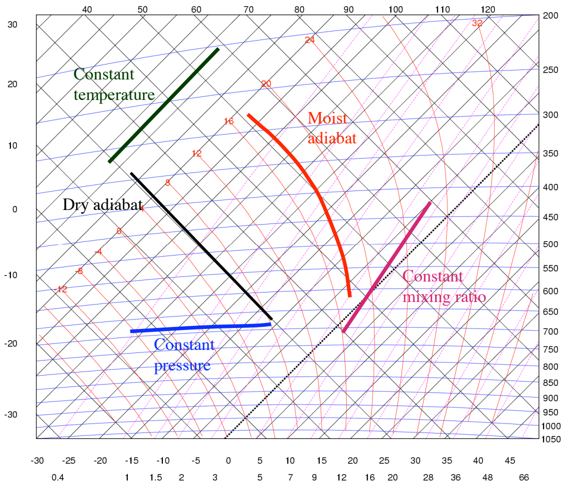
Tephigram



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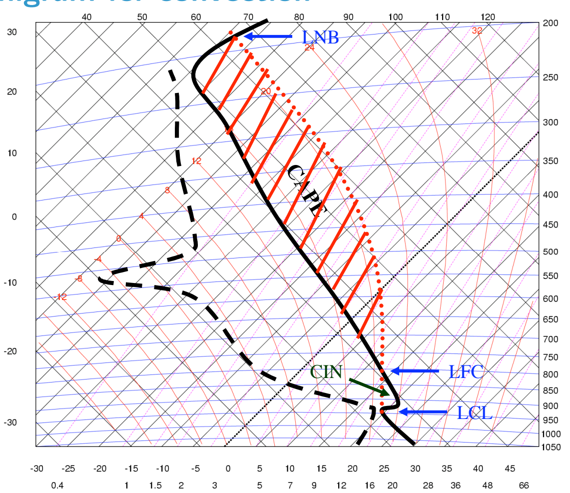
Tephigram for convection



dynamics (dyn) / thermodynamics (th)

warming of air parcels:

- downward motion (adiabatic compression) (dyn)
- condensation of water vapour on droplets (th)
- freezing of droplets (th)
- deposition of water vapour on ice crystals (th)

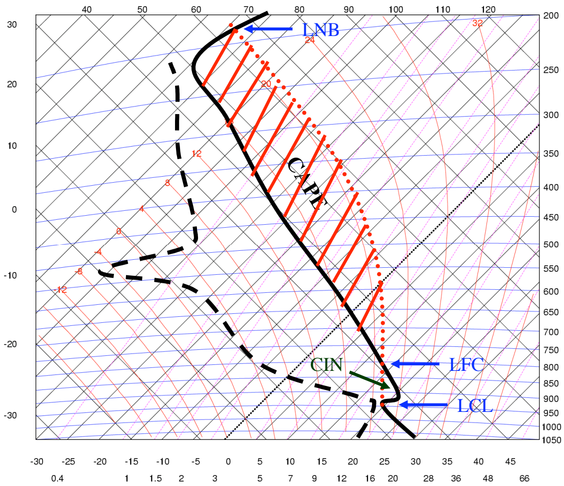
cooling of air parcels:

- upward motion (adiabatic expansion) (dyn)
- evaporation of droplets (th)
- sublimation of ice crystals/graupel/hail (th)
- melting of ice crystals/graupel/hail (th)

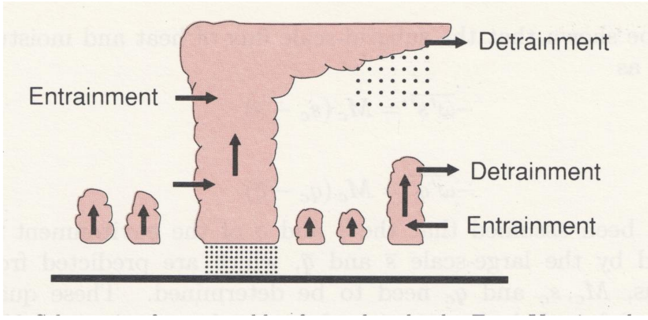
Effect of convection

- Moistening of the troposphere:
  resulting profile ≈ moist adiabatic profile
- Consumption of CAPE, depending on entrainment
- Effects on large scale: Warming of the environment

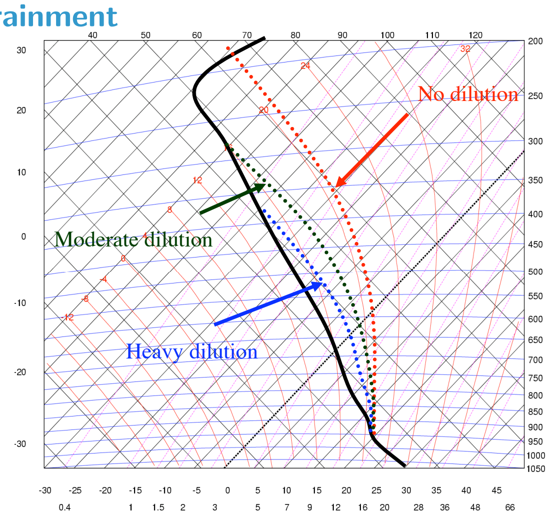
Moistening



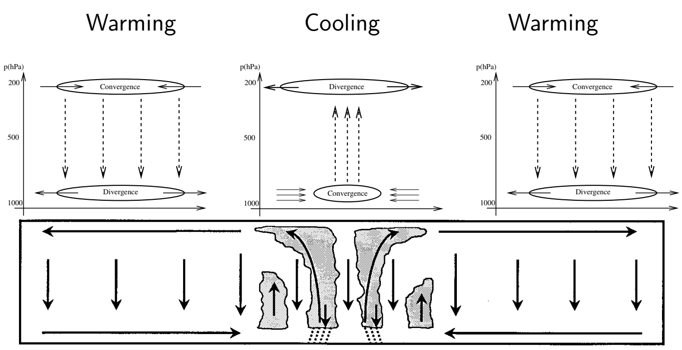
Entrainment



Entrainment



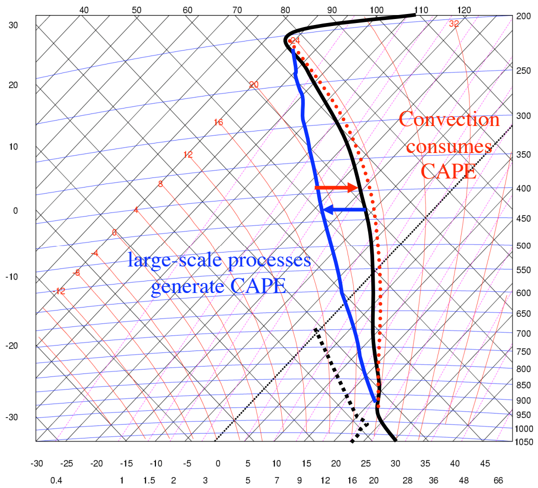
Large scale effects



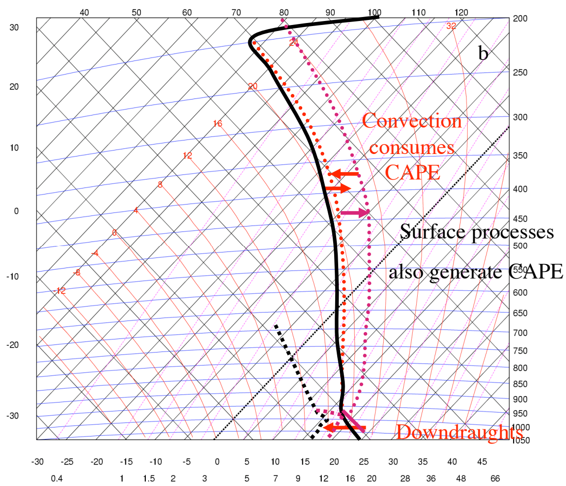
Triggering of convection

- To overcome CIN:
  - Vertical motion (large scale, mountains ...)
  - Surface processes (heat/moisture flux)
  - Moisture convergence (?)
- Generation of conditional instabilities (radiation/surface processes)
- Quasi Equilibrium Theory

Radiation



Surface



Quasi equilibrium

Different time scales for

- Generation of CAPE (i.e. conditional instabilities) by large scale processes
- Consumption of CAPE by convection

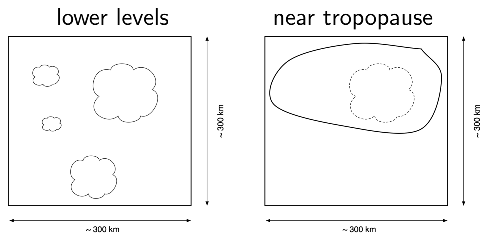
Assumption (Arakawa and Schubert, 1974; Emanuel et al., 1994):

$$\frac{\partial \mathrm{CAPE}}{\partial t} \approx 0 \qquad (1)$$

statistical balance between generation and consumption of CAPE

Multiscale problem Convection

- Convective processes on different scales (1μm to 100 km)
- Convective cells small compared to grid cells of large scale models, i.e. convection is subgrid process



$\Rightarrow$ need of parameterisations

Cumulus mass flux I

Relation between subgrid scale heat/moisture fluxes to cloud processes:

- Population of cumulus clouds
- Collective behaviuor of population described by bulk cloud properties
- Cumulus cloud mass flux = amount of air transported in the vertical direction of the (bulk) cloud

For pressure coordinates:

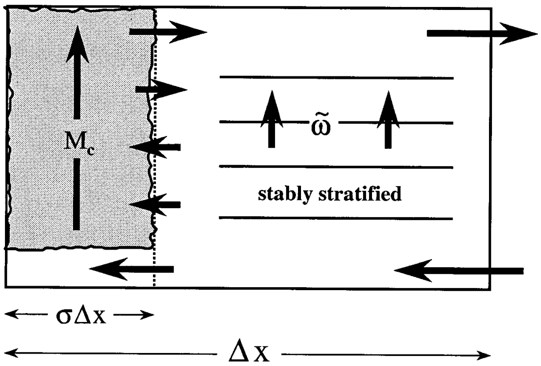
$$\text{cloud mass flux: } M_c := -\sigma\omega_c; \text{environment: } M_e := -(1-\sigma)\omega_e \qquad (2)$$

such that $\overline{M} = M_c + M_e$ total flux of large scale region

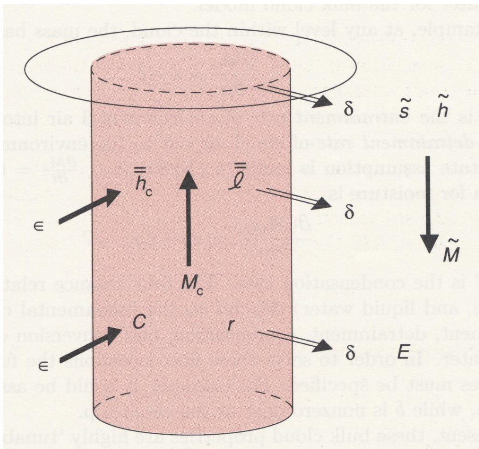
For entrainment/detrainment:

$$\frac{\partial (M_c)}{\partial p} = \epsilon - \delta \qquad (3)$$

Cumulus mass flux II



Cumulus mass flux III



Types of parameterisations

Cumulus parameterisation problem

Link between "large scale processes" and "convective processes" is called "closure"

Different types of parameterisations based on different closure assumptions:

- Adjustment schemes (e.g. Manabe et al., 1965)
- Closure based on moisture convergence (e.g. Kuo, 1965)
- Closure based on simple cloud model (e.g. Kurikara, 1973)
- Closure based on quasi-equilibrium (e.g. Arakawa and Schubert, 1974; Emanuel, 1989, see following lectures)

Main questions:

- How is convection initiated?
- If cumulus mass flux is used, how is the flux determined?

Historical remark

Almost all cumulus parameterisation schemes have their origin in the attempt of simulating tropical cyclones correctly.

Adjustment schemes I

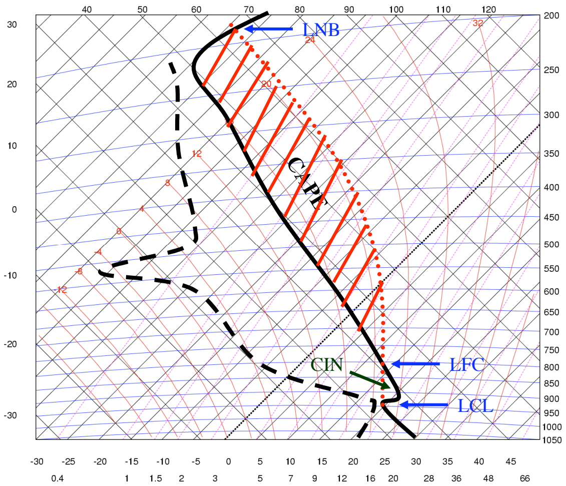
Observations: Convection tends to adjust vertical profiles of temperature/humidity to moist adiabatic profiles (lapse rate Γ_m, saturated)

Parameterisation: At any level with

- lapse rate greater than Γ_m
- specific humidity exceeding saturation

$\Rightarrow$ adjustment to moist adiabatic lapse rate, saturation, excess humidity is assumed to rain out.

Adjustment schemes II



Adjustment schemes III

Advantages:

- Very simple scheme (easy to implement, not expensive)
- Based on observations

Disadvantages:

- Adjustment instanteneous, no life cycle
- Adjustment is local and does not depend on large scales/surface processes

Adjustment schemes IV

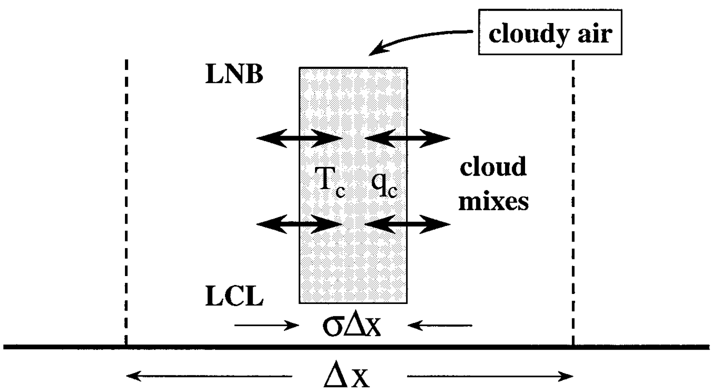
Different approaches

- Adjustment to different reference profiles of temperature and relative humidity (e.g. different profiles for shallow and deep convection)
- Different "thresholds", e.g. RH need not to be above 100% ...

Timescales

- adjustment immedeately
- relaxation time scale

Moisture convergence I



Moisture convergence II

- Deep convection occurs in regions with
  1. conditional instabilities
  2. low-level moisture convergence
- Cumulus clouds formed from boundary layer air (moist adiabatic profile)
- Clouds extend from LCL to LNB
- Clouds exist only momentarily before they mix totally with their environment
- Mass flux is proportional to moisture convergence

Moisture convergence III

Moisture convergence = mass flux:

$$C = -\frac{1}{g}\int_{p_{LNB}}^{p_{LCL}} \nabla_p \circ (\mathbf{u}q)dp \quad \underbrace{-\frac{\omega_b q_b}{g}}_{\text{cloud base flux}} \quad + F_{q_s} \tag{4}$$

Heating rate:

$$\frac{dQ_c}{dt} = \frac{\sigma}{\Delta t} c_p (T_c - T_o) \quad \text{for} C < 0, T_c > T_o \tag{5}$$

Fractional area of grid cell covered by convective cell:

$$\sigma = \frac{C \Delta t}{W_1 + W_2} \tag{6}$$

W_1, W_2=amount of moisture required to raise environment temperature and humidity to moist adiabatic values T_c, q_c

$$W_1 = \frac{1}{g\Delta t}\int_{p_{LNB}}^{p_{LCL}} \frac{c_p}{L}(T_c - T_o)dp, \quad W_2 = \frac{1}{g\Delta t}\int_{p_{LNB}}^{p_{LCL}} (q_c - q_o)dp \tag{7}$$

Moisture convergence IV

Rate of moistening due to mixing:

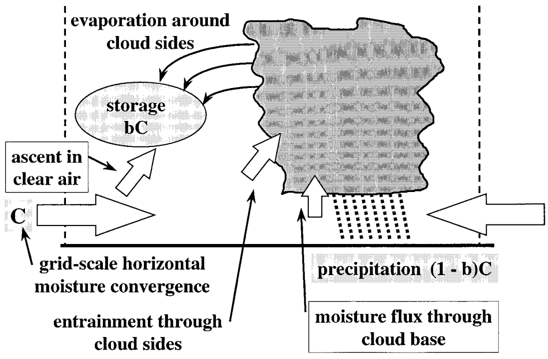
$$\frac{dW_c}{dt} = \frac{\sigma(q_c - q)}{\Delta t} \tag{8}$$

Problem: Scheme excessively moistens the atmosphere
Extended version (Kuo, 1974): Rate of moistening is equal to small fraction b of the precipitation rate P, i.e.:

$$\frac{dW_c}{dt} = \int_0^\infty \frac{\partial \rho q}{\partial t} dz = bP \tag{9}$$

Problem: How to determine b? Sometimes linked to large scale relative humidity.

Moisture convergence V



Moisture convergence VI

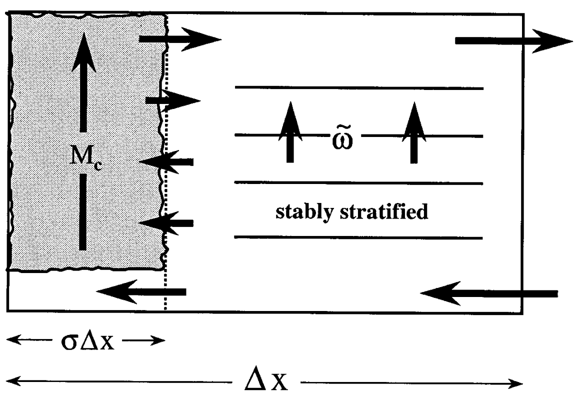
Advantages:

- relatively simple
- link to large scale environment

Disadvantages:

- concept of moisture convergence is really questionable (Emanuel, 1994)
- no realistic moistening

Simple cloud model I



Simple cloud model II

Assumptions:

- Ensemble of buoyant elements, independent of each other
- Bulk cloud for ensemble (mass flux assumption)
- Steady one-dimensional cloud model (entraining plume), cover small fraction σ
- Immediate fallout of rain

For numerical model: quasi 2D setup

- single cloud column with entrainment, no downdrafts
- surrounded air is stably stratified

Systems of equations for grid-averaged temperature and moisture closed by mass flux

Simple cloud model III

Statistical ensemble of air bubbles of different sizes released per unit time

Mass flux distribution = dispatcher function

Example for mass flus: mass flux = mean resolvable vertical velocity at top of subcloud layer

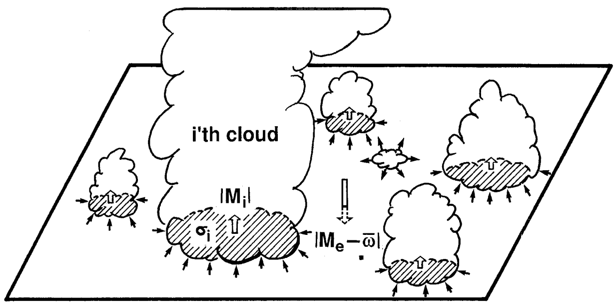
Advantages:

- more physically based, ensemble of clouds
- still simple

Disadvantages:

- Derivation of mass flux
- Effect of entrainment/detrainment insufficient

Quasi equilibrium I



Quasi equilibrium II

Quasi equilibrium:

$$\frac{\partial \mathrm{CAPE}}{\partial t} \approx 0$$

generation (large scale) $\approx$ consumption (convection)

Assumptions:

- cumulus clouds = ensemble of entraining plumes
- each cloud has the same cloud base height
- each cloud has different but constant entrainment rate λ
- cloud top depends on entrainment (LNB)

Concept of work function:
work function = amount of work done by buoyancy in each cloud type per unit cloud base mass flux
For no entrainment: work function = CAPE

Quasi equilibrium III

Work function:

- depends on large scale environment (dynamics and thermodynamics)
- increases as a result of destabilizing large scale processes (radiative cooling, vertical motion, surface heat/moisture flux)
- decreases as a result of convection (warming by subsidence)

Closure obtained by setting time rate of change of work function =0 for each cloud type $\Rightarrow$ determining of cloud base mass flux

Quasi equilibrium IV

Advantages:

- based on quasi equilibrium, link to large scale environment
- different cloud types (spectrum) with different cloud tops/entrainment rates

Disadvantages:

- very complicated
- very expensive

Still problems with cumulus convection not driven by boundary layer or with shallow convection, e.g. life time of convection etc. ...