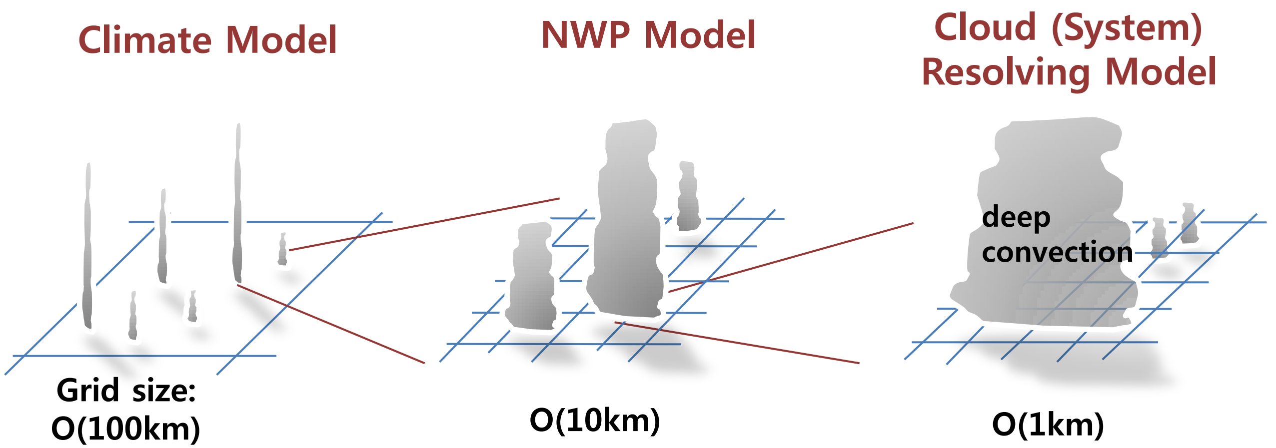
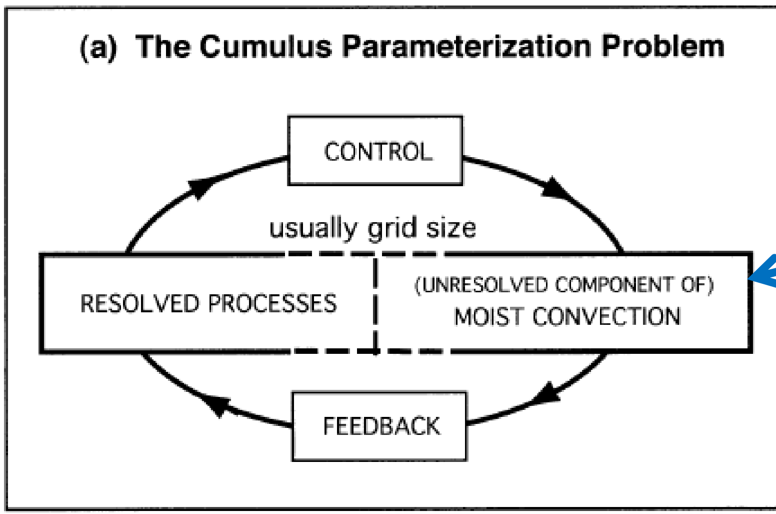
Typical (horizontal) Resolutions

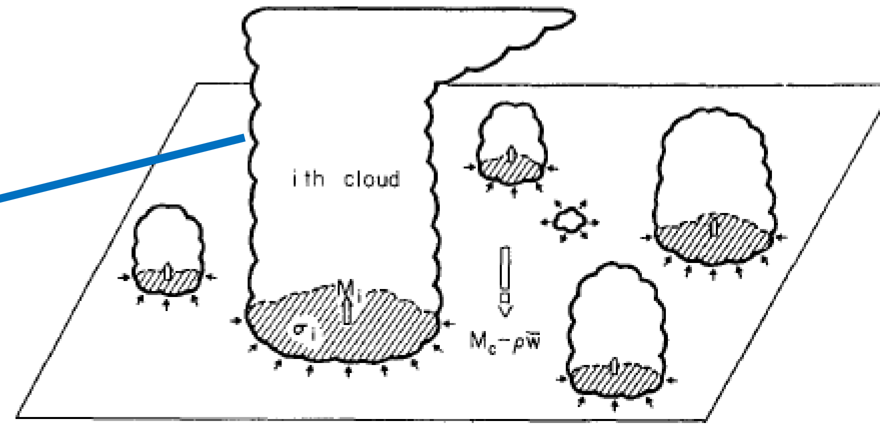


Cumulus parameterization

- Representation of **effect** of cumulus ensemble in climate model which has grid size not enough small to resolve them



Arakawa (2004)



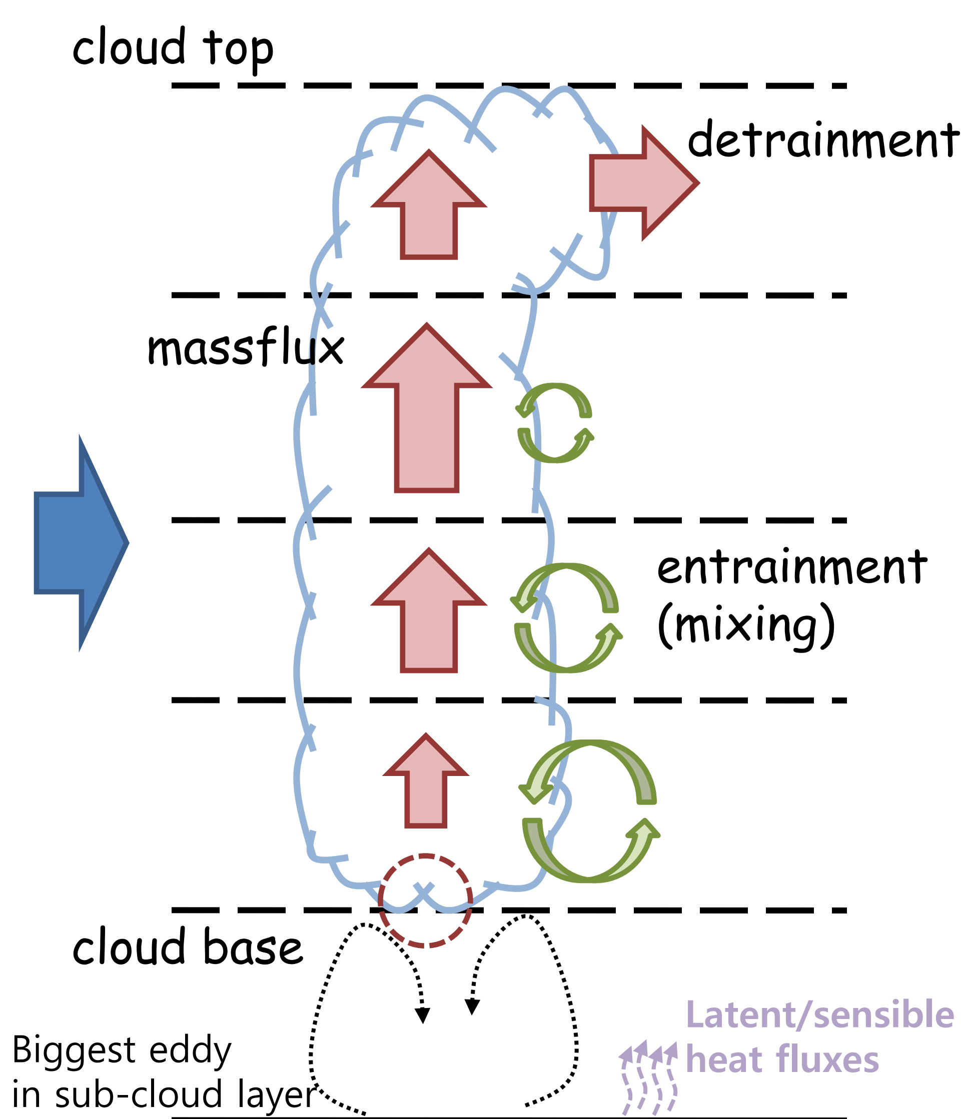
Arakawa and Schubert (1974)

- **We don't need parameterizations if we can resolve**

Cumulus cloud in nature

www.usatoday.com/weather/wcumulus.htm

Cumulus cloud in climate model



AMIP (Slingo et al. 1996)

Model	Deep convection
BMRC	Kuo
CCC	MCA
CNRM	Bougeault
CSIRO	MCA
CSU	AS+MCA
ECMWF	Tiedtke
GLA	AS
GSFC	RAS
LMD	Kuo+MCA
MRI	AS
NCAR	Hack
NMC	Kuo/Tiedtke
RPN	Kuo
UGAMP	Betts-Miller
UKMO	Gregory

CMIP3 (Lin et al. 2006)

Model	Deep convection
GFDL CM2.0	RAS
GFDL CM2.1	RAS
NCAR CCSM3	ZM
NCAR PCM	ZM
GISS-AOM	Russell et al.
GISS-ER	Del Genio and Yao
MIROC-hires	Pan and Randall
MIROC-medres	Pan and Randall
MRI	Pan and Randall
CCCMA	ZM
MPI	Tiedtke
IPSL	Emanuel
CNRM	Bougeault
CSIRO	Gregory and Rowntree

*red: mass flux scheme

Where are they in the equations?

❖ Large-scale budget equations for dry static energy and water vapor

Tiedtke (1989)

$$\frac{\partial \bar{s}}{\partial t} + \bar{\vec{v}} \cdot \nabla \bar{s} + \bar{w}\frac{\partial \bar{s}}{\partial z} = -\underline{\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\left[M_u s_u + M_d s_d - (M_u + M_d)\bar{s}\right]} - \frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\left(\bar{\rho}\overline{w's'}\right)_{tu} + \underline{L(\bar{c} - \bar{e})} + \overline{Q_R}$$

$$\frac{\partial \bar{q}}{\partial t} + \bar{\vec{v}} \cdot \nabla \bar{q} + \bar{w}\frac{\partial \bar{q}}{\partial z} = -\underline{\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\left[M_u q_u + M_d q_d - (M_u + M_d)\bar{q}\right]} - \frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\left(\bar{\rho}\overline{w'q'}\right)_{tu} - \underline{(\bar{c} - \bar{e})}$$

— Cumulus parameterization

- M : mass flux
- u: updraft
- d: downdraft

$M_{u/d}, s_{u/d}, q_{u/d}, c, e$ **: determined by cumulus parameterization**

Cumulus Momentum Transport

- Dynamic Impacts

Shapiro and Stevens (1980)

fractional cloud coverage

$$\text{momentum } \mathbf{X}_c = -M_c \frac{\partial \bar{\mathbf{v}}}{\partial p} + \delta(\mathbf{v}_D - \bar{\mathbf{v}}) + \sigma\left(\frac{1}{\rho} \nabla p^*\right)$$

acceleration

Momentum Budget Residual:

$$\begin{aligned} \mathbf{X} = (X, Y) &\equiv \frac{\partial \bar{\mathbf{v}}}{\partial t} + \bar{\mathbf{v}} \cdot \nabla \bar{\mathbf{v}} + \bar{\omega} \frac{\partial \bar{\mathbf{v}}}{\partial p} + \nabla \bar{\phi} + \lambda \mathbf{k} \times \bar{\mathbf{v}} \\ &= -\nabla \cdot \overline{\mathbf{v}'\mathbf{v}'} - \frac{\partial \overline{\mathbf{v}'\omega'}}{\partial p}, \end{aligned} \quad (3)$$

where ϕ is the geopotential height, λ the Coriolis parameter, $\bar{\ }$ the area ensemble mean, and $'$ the convective-scale components.

Cloud model for updraft
:entraining-detraining plume model

❖ For normalized mass flux (η), moist static energy(h), total water vapor(q^t), and vertical velocity (w)

$$\frac{\partial \eta}{\partial z} = (\varepsilon - \delta)\eta$$

$$M_u = \eta M_b$$: Closure

$$\frac{\partial h_u}{\partial z} = -\varepsilon\left(h_u - \bar{h}\right)$$

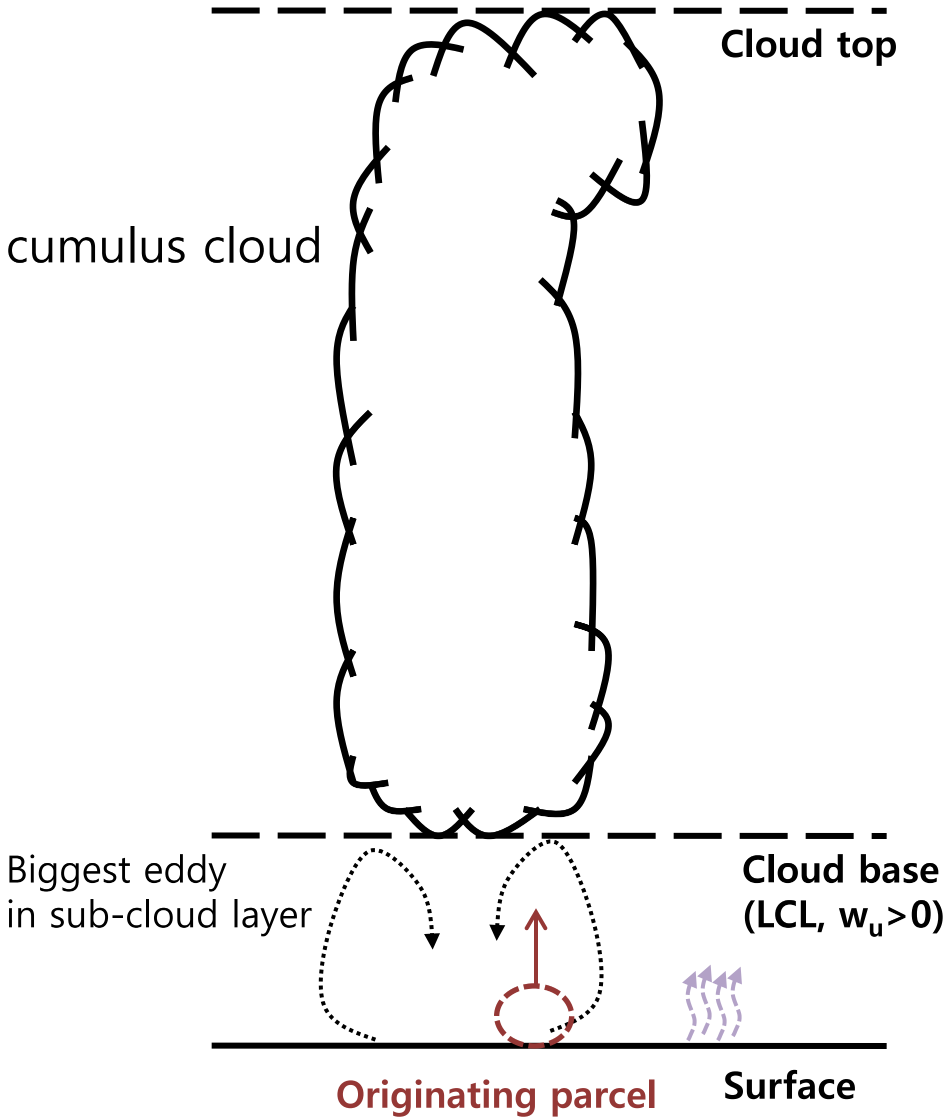
$$\frac{\partial q_u^t}{\partial z} = -\varepsilon(q_u^t - \overline{q^t}) - g_p$$

$$\frac{1}{2}\frac{\partial w_u^2}{\partial z} = aB_u - b\varepsilon w_u^2$$

Buoyancy (↑ B_u)

$$B_u = \frac{g}{\overline{T_v}}\left(T_{v\,u} - \overline{T_v}\right) - gl_u$$

Cloud model



❖ **Equations for updraft properties**

$$\frac{\partial \eta}{\partial z} = (\varepsilon - \delta)\eta$$

$$\frac{\partial h_u}{\partial z} = -\varepsilon\left(h_u - \bar{h}\right)$$

$$\frac{\partial q_u^t}{\partial z} = -\varepsilon(q_u^t - \overline{q^t}) - g_p$$

$$\frac{1}{2}\frac{\partial w_u^2}{\partial z} = aB_u - b\varepsilon w_u^2$$

❖ **Entrainment rate (sub-cloud layer)**

$$\varepsilon \cong c_e \frac{1}{z}, c_e = 0.55$$

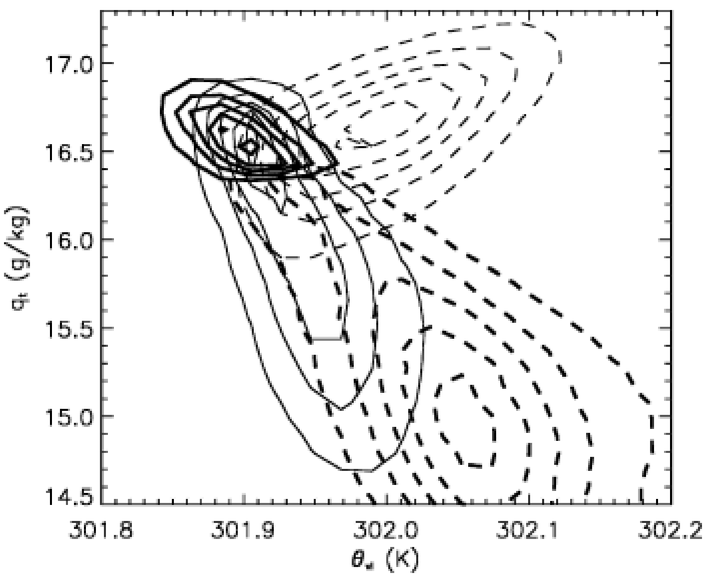
Siebesma and Teixeira (2000)

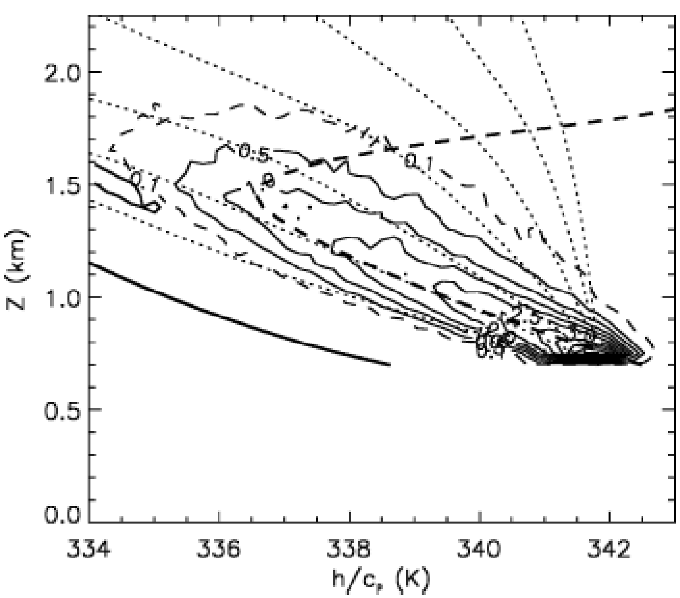
❖ **Entrainment rate (cloud layer)**

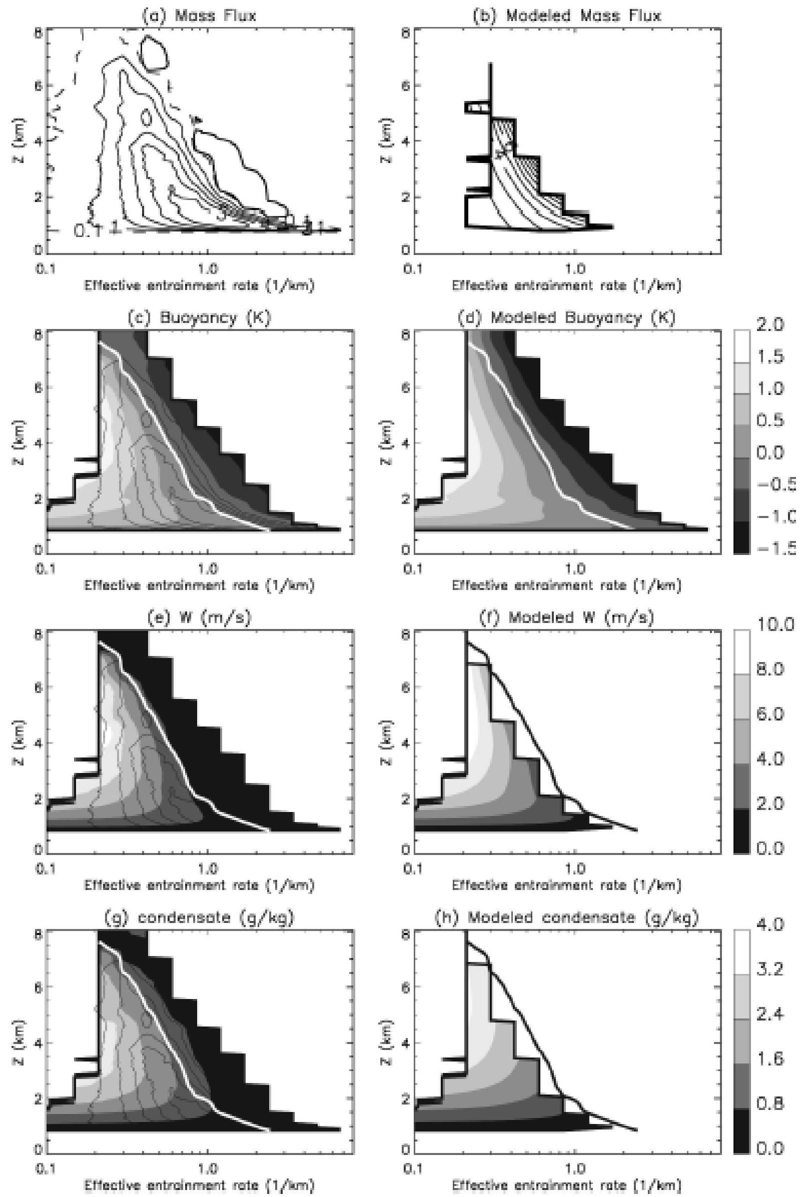
$$\varepsilon = \frac{C_\varepsilon a}{{w_u}^2} B_u$$

Gregory (2001)

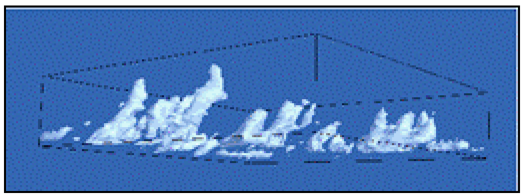
Kuang and Bretherton (2006) – CSRM data

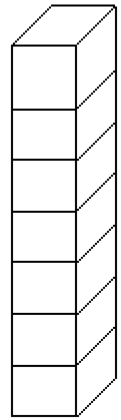


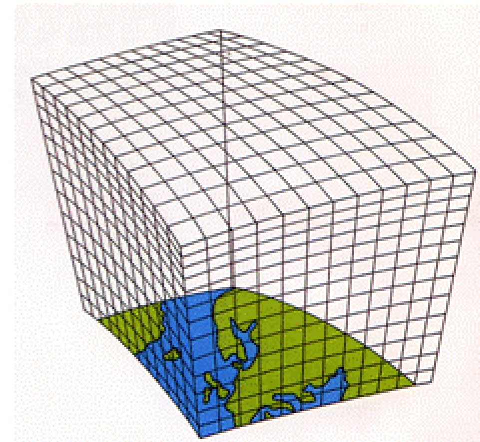




Climate Model Development strategy







Large Eddy Simulation (LES) Models

Cloud Resolving Models (CRM)

Single Column Model

Versions of Climate Models

3d-Climate Models

NWP's

Observations from

Field Campaigns

Global observational

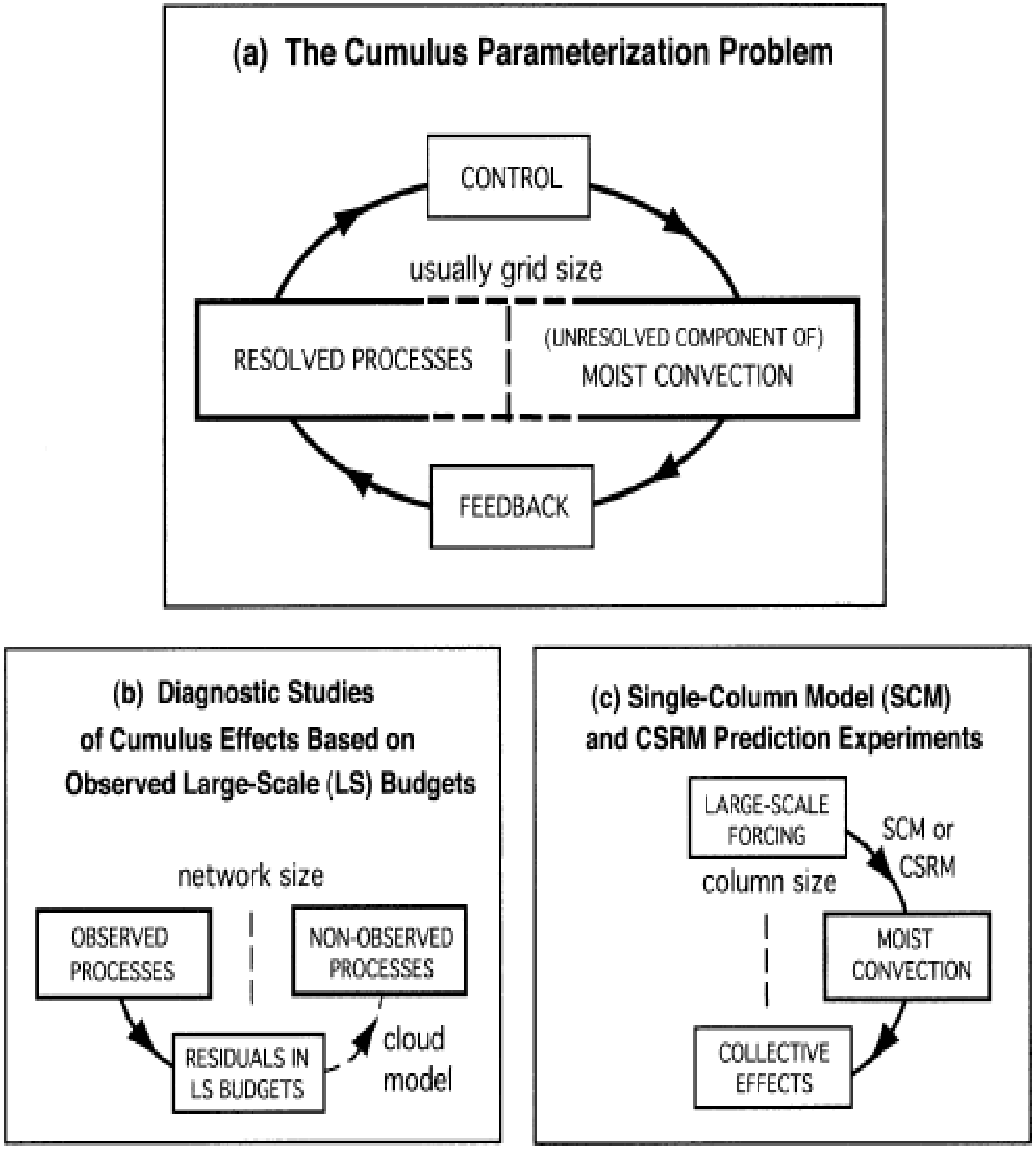
Data sets

Development

Testing

Evaluation

http://www.knmi.nl/~siebesma/



Arakawa (2004)

Some Classical schemes for GCM:

- Cumulus (unresolved) effects directly related to resolved processes (e.g., Kuo 1965, 1974)

- Instantaneous adjustment of vertical profiles to quasi-neutral states. (e.g., Manabe et al. 1965; Arakawa & Schubert 1974; Lord et al. 1982)

- Relaxed, delayed or triggered adjustment of vertical profiles toward quasi-neutral states. (e.g., Betts and Miller 1986; Emanual 1991; Moorthi and Suarez 1992; Randall and Pan 1993)

Hierarchy of data for parameterization development

- **Level 0** (forcing data to both SCM/CSRM)
  - Horizontal/vertical advection of T, q, ql, qi, qa
  - Any kinds of error statistics are highly required (e.g. ensemble of forcing data)

- **Level 1** (results from model, not from parameterization)
  - Profiles of T, q, ql, qi, qa (grid mean/sub-grid scale distribution)
  - Surface/TOA radiation budget
  - Cloud type classification as function of MJO regime
  - Process-oriented diagnostics (emergency properties): through data assimilation?

More useful For development

- **Level 2** (bulk properties of parameterized cumulus)
  - Mass flux ("grid averaged" in-cloud density, vertical velocity, and cloud fraction)
  - Cloud base, echo top height
  - Well-validated CSRM data could be also used

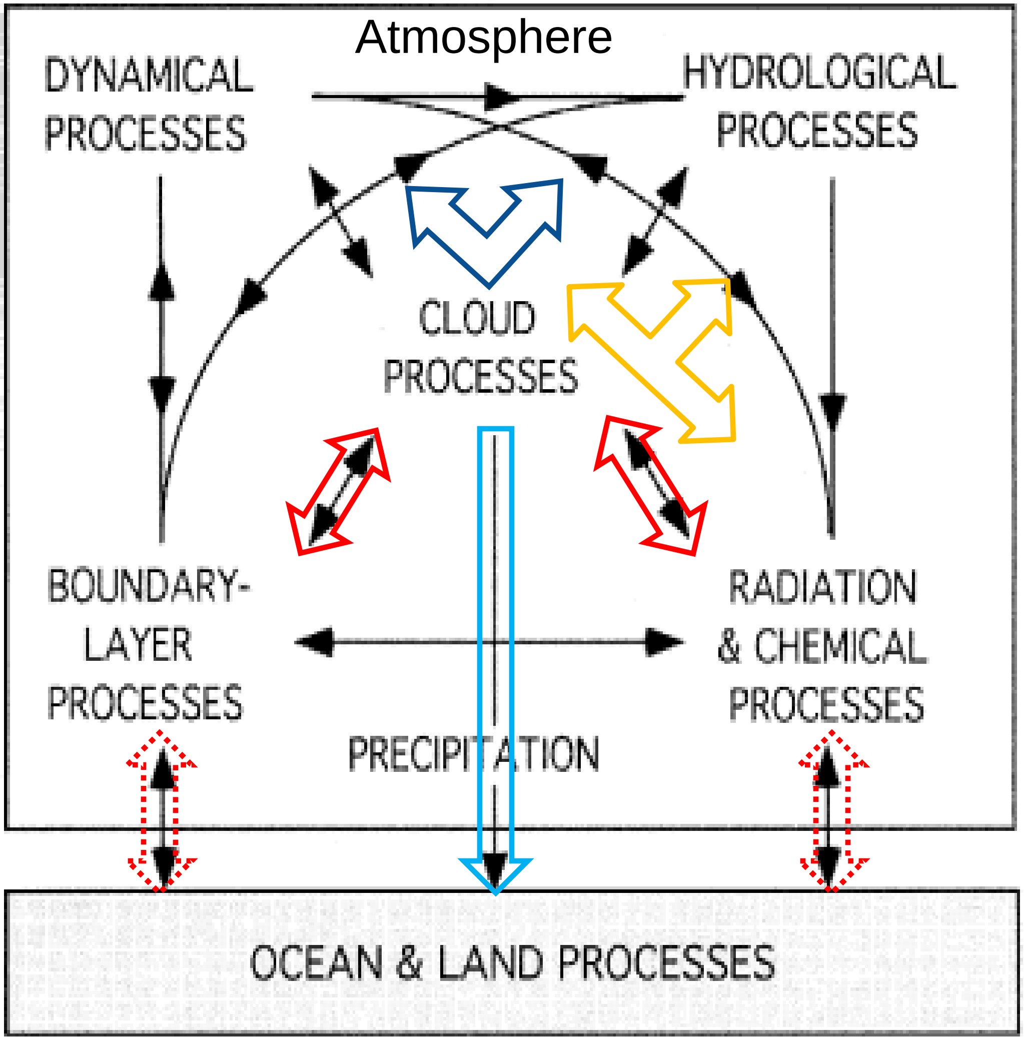
- **Level 3** (inside parameterized cumulus)
  - Entrainment/detrainment rate, buoyancy, plume radius, vertical velocity, T, q (Raman lidar?)
  - TKE in boundary layer (sub-grid scale distribution of vertical velocity)
  - Microphysical properties as source of stratiform anvil
  - Mostly, well-validated CSRM data should be used (assumed low possibility this could be observed directly in a useful manner)
  - Some samples (simultaneous observations of in-cloud T, q)

Issues

- Representative scale
  - From point to averaged: time-averaging (maybe consistent to stationary assumption)
- Do we need any practices to derive required quantity before DYNAMO?

Clouds in the climate system

Cumulus Convection Plays a Central Role



1. Coupling through heat of condensation/evaporation; Redistribution of sensible/ latent heat and momentum
2. Reflection, absorption, and emission of radiation
3. Influencing ground hydro. processes via precipitation
4. Influencing couplings of the atmosphere and ocean (ground) via modification of radiation and PBL processes.

(Arakawa 1975, 2004)

Flash Back: The Representation of Cumulus Convection in Numerical Weather Prediction (NWP) and General Circulation Models (GCMs)

- The representation of cumulus convection is also known as cumulus parameterization.
- Updated definition of the cumulus parameterization problem:
  The problem of formulating the statistical effects of moist convection to obtain a closed system for predicting weather and climate.
  (Arakawa 2004)

Cumulus parameterization was introduced in the early 1960s

Charney and Eliassen (1964)
"Since a self-consistent theory of turbulent cumulus convection in an anisotropic mean field does not exist, one is forced to parameterize the process"

Manabe et al. (1965)
"...we used a simple convective adjustment of temperature and water vapor as a substitute for the actual convective process."

General Circulation Modeling; the first application of the concept to a moist numerical model of the atmosphere.

Ooyama (1964)
"... it is hypothesized that the statistical distribution and mean intensity of the cloud convection are controlled by the large-scale convergence of the warm and moist air in a surface layer,..."

Tropical Cyclone Modeling

Ooyama (1969) is recognized as the first successful simulations of tropical cyclone development.

Impacts of randomness on a dynamical system, an example with Lorenz 63

Tung et al. (2008)

$$\frac{dx}{dt} = -\sigma(x - y),$$

$$\frac{dy}{dt} = rx - y - xz + D\eta(t),$$

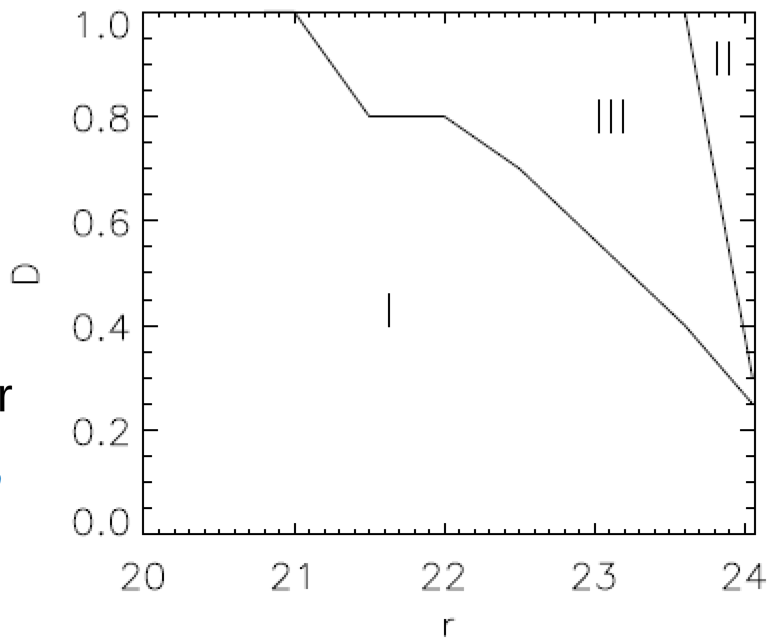
$$\frac{dz}{dt} = xy - bz,$$

where $D\eta(t)$ *is a white Gaussian noise term with* mean 0 and variance D^2, *σ = 10, and b = 8/3.*

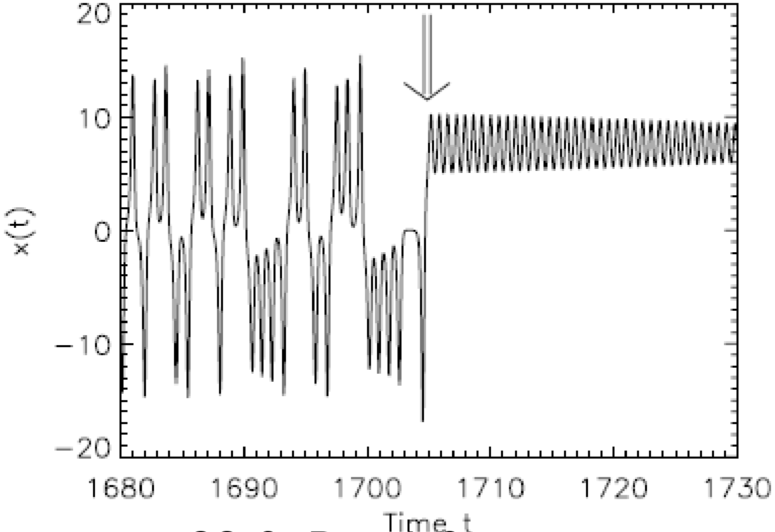
for *r* $\in$ *(24.06, 24.74),* system has two stable fixed points and a strange attractor

For r $\in$ *(13.926, 24.06), the clean system* has two stable fixed point attractors *and metastable chaos.*

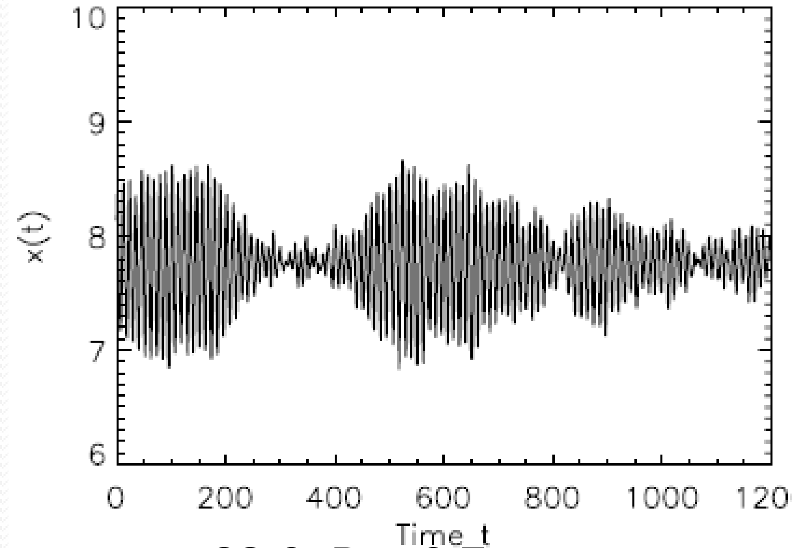
A phase diagram *D versus r illustrating the observed* asymptotic dynamics of the noisy Lorenz system for *r* ≤ 24*.05*.
Region I: noisy dynamics around the two fixed point solutions;
Region II: noise-induced chaos;
Region III: intermittency.



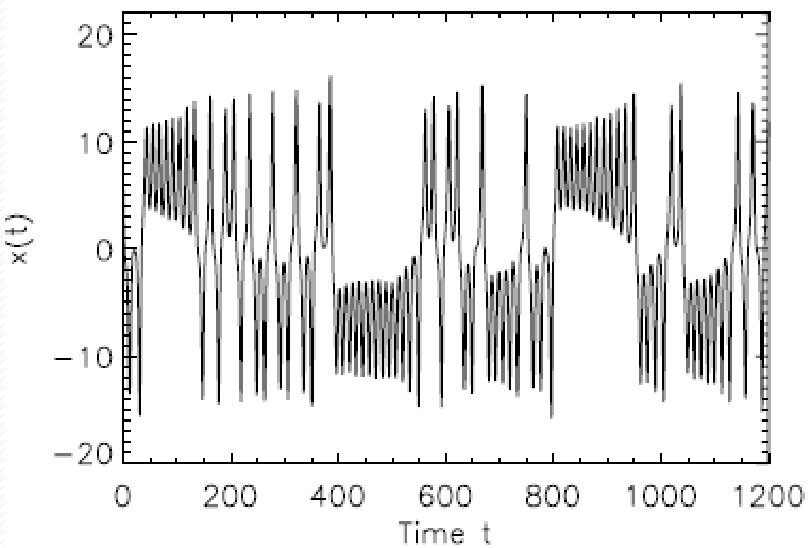
r = 23.5, D = 0
Metastable chaos



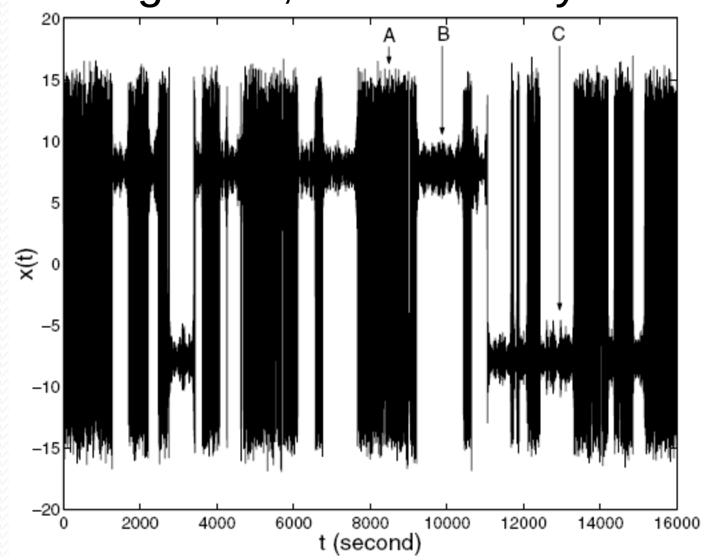
R = 23.6, D = 0.2
Region I, noisy fixed point



r = 23.6, D = 1.0
Region II, chaos



r = 23.6, D = 0.7
Region III, intermittency



Some thoughts from the previous exercise

- The unresolved organized cumulus convection may act like randomness on the resolved scales in a NWP model or GCM.
- The interaction may alter the solutions of the model dramatically, depending on the strength of the noise.
- The first step in solving the cumulus parameterization problem is to form a principal closure assumption which constrains the existence and overall intensity of cumulus activity.

A very useful additional closure assumption would be a 'cloud model'

- Thermodynamic Impacts

Ooyama (1971), Arakawa and Schubert (1974), Yanai et al. (1973)

$\overline{M}$ large-scale mass flux

M_C cloud mass flux

δ cloud-top detrainment

temperature $$Q_{1c} = -M_c \frac{\partial \bar{s}}{\partial p} + \delta(s_D - \bar{s} - L l_D)$$

moisture $$Q_{2c} = L M_c \frac{\partial \bar{q}}{\partial p} - L\delta(q_D - \bar{q} + l_D)$$

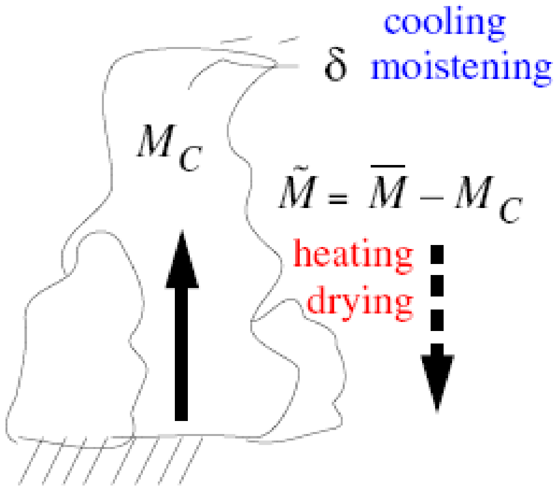
- Dynamic Impacts

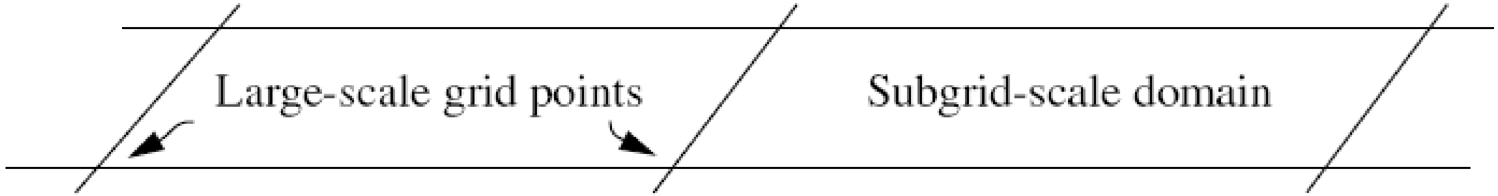
Shapiro and Stevens (1980)

momentum $$\mathbf{X}_c = -M_c \frac{\partial \bar{\mathbf{v}}}{\partial p} + \delta(\mathbf{v}_D - \bar{\mathbf{v}}) + \sigma\left(\frac{1}{\rho}\nabla p^*\right)$$

acceleration

fractional cloud coverage





Diagnostic studies of cumulus activity based on observed large-scale budgets

Apparent Heat Source: (Yanai et al. 1973)

1st law of thermodynamics

$$Q_1 \equiv c_p\left(\frac{p}{p_o}\right)^{\kappa}\left(\frac{\partial\overline{\theta}}{\partial t}+\overline{\mathbf{v}}\cdot\nabla\overline{\theta}+\overline{\omega}\frac{\partial\overline{\theta}}{\partial p}\right)$$
$$= Q_R + L(\overline{c}-\overline{e}) - \nabla\cdot\overline{s'\mathbf{v}'} - \frac{\partial\overline{s'\omega'}}{\partial p} \qquad (1)$$

Apparent Moisture Sink:

Mass conservation of water contents

$$Q_2 \equiv -L\left(\frac{\partial\overline{q}}{\partial t}+\overline{\mathbf{v}}\cdot\nabla\overline{q}+\overline{\omega}\frac{\partial\overline{q}}{\partial p}\right)$$
$$= L(\overline{c}-\overline{e}) + \nabla\cdot\overline{q'\mathbf{v}'} + \frac{\partial\overline{q'\omega'}}{\partial p}, \qquad (2)$$

θ: potential temperature; ω the vertical p-velocity ; $p_0 = 1000$ hPa ; $\kappa = R/c_p$ with R the gas constant of dry air ; Q_R the radiative heating rate ; c and e are the rates of condensation and evaporation (of cloud water) per unit mass of air.

ANALYSIS OF RELEASED HEAT BY CONDENSATION

$$Q_1 = \frac{c_p}{\left(\frac{p_0}{p}\right)^{\frac{\gamma-1}{\gamma}}}\left(\frac{\partial\theta}{\partial t} + \nabla(\theta \mathbb{V}) + \frac{\partial}{\partial p}(\theta\omega)\right)$$

$$Q_2 = -L\left(\frac{\partial q}{\partial t} + \nabla(q\mathbb{V}) + \frac{\partial}{\partial p}(q\omega)\right)$$

θ : potential temperature

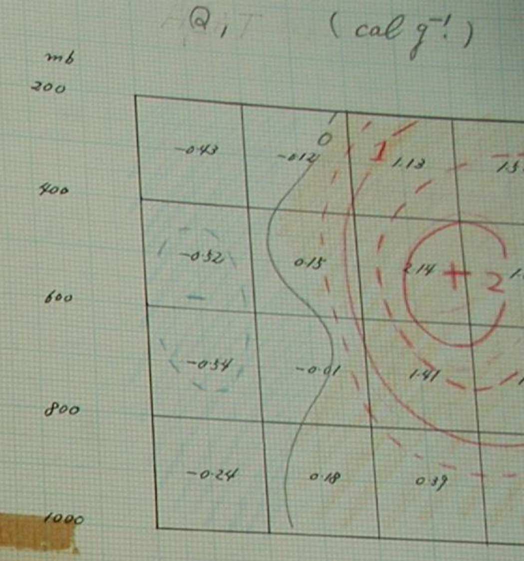
q : mixing ratio of water vapour

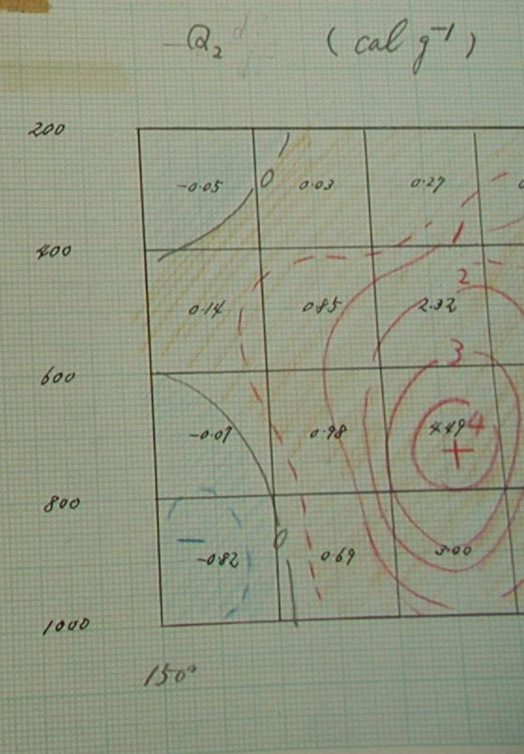
1) 3-dimensional distribution of Q_1 and Q_2

2) horizontal distribution of $\frac{1}{g}\int Q_1\,dp$ and $\frac{1}{g}\int Q_2\,dp$

3) comparison of $-\frac{1}{g}\int\frac{dq}{dt}\,dp$ and observed precipitation.

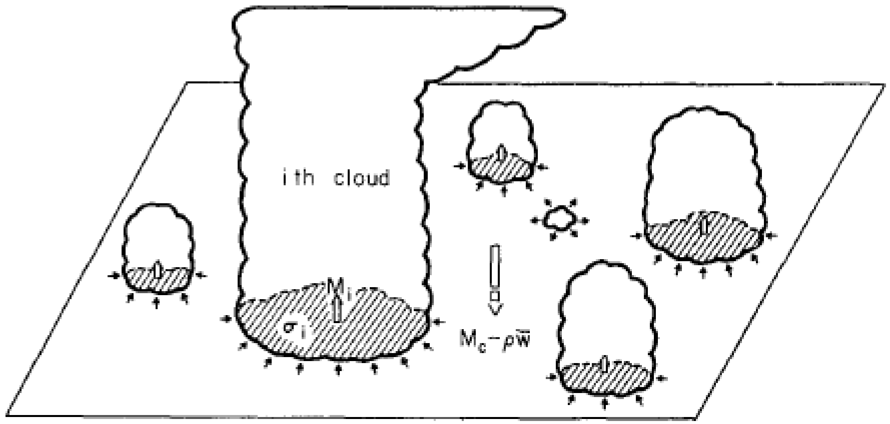
4) total heat budget of "Verification area".



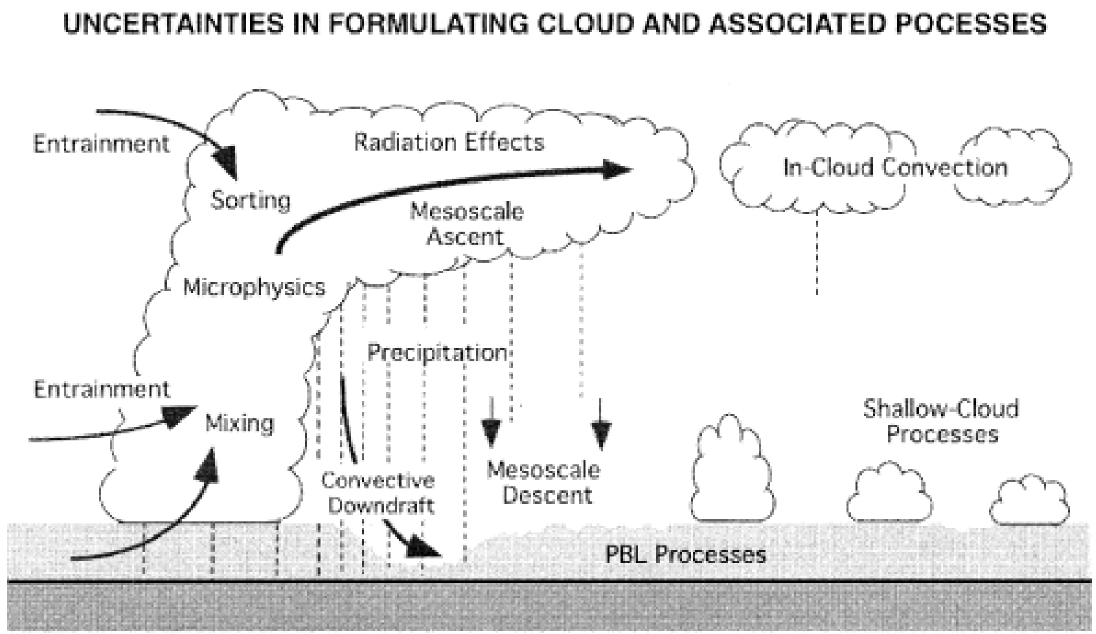


ca. 1960

Challenges remain…



Arakawa and Schubert (1974)



Arakawa (2004)

Final Thoughts

- Ooyama (1982, 1987)

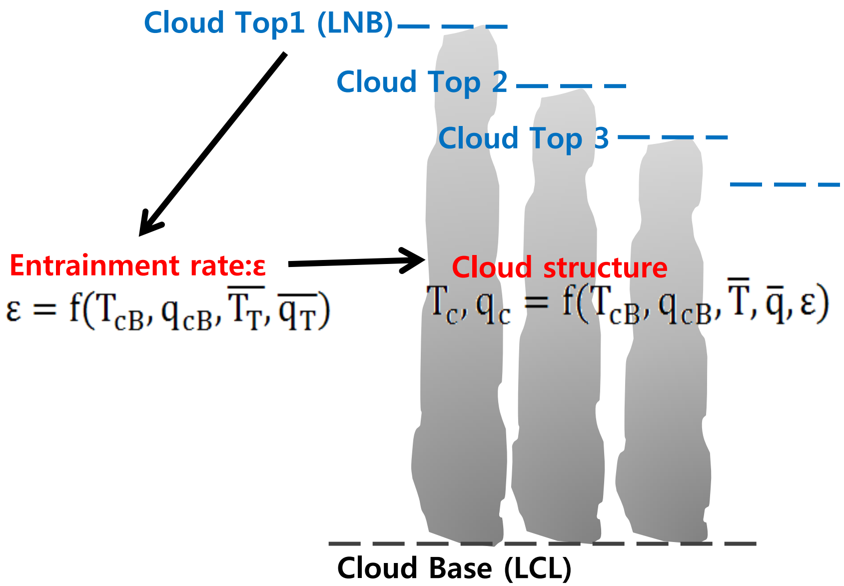
  "With further advances in numerical modeling, the interest in tropical cyclone research shifted from conceptual understanding of an idealized system to quantitative simulation of the detail of real cyclones…"

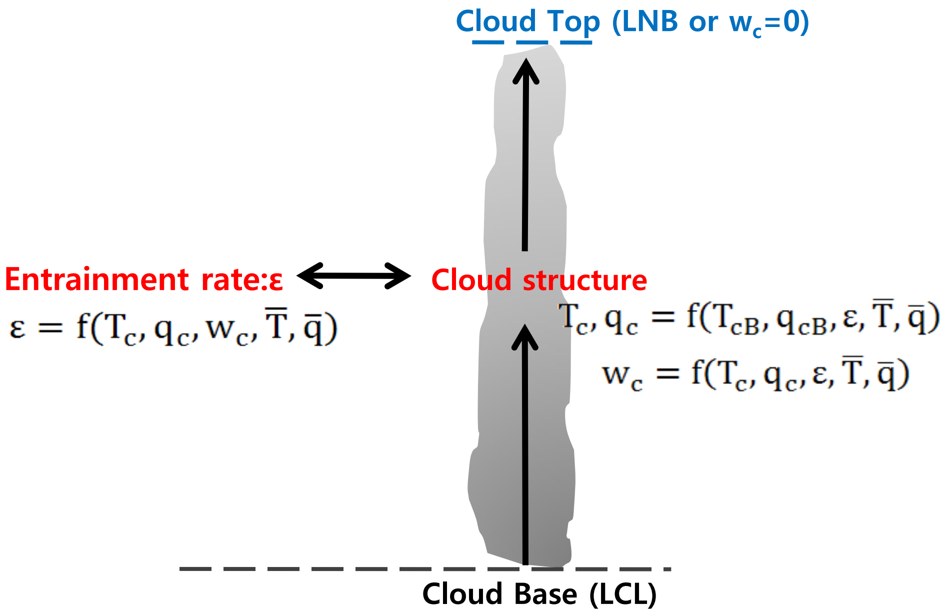
  "… the parameterization of convection is a technical problem of modeling and not at all an essential requirement for understanding tropical cyclones."

  "… one may wonder if all the exercises with parameterized convection were an unfortunate detour in the history of tropical cyclone modeling."

- In fact, concepts and understanding do not automatically emerge from high-resolution modeling.

Cloud model of mass flux cumulus parameterizations





❖**Entrainment rate (passive)**
➔ smaller in deeper cloud

❖**Entrainment rate (active)**
➔ Determines cloud top

❖ **Minimum entrainment rate**
➔ turns off deep convection in dry column

❖ **Enhancing entrainment rate**
➔ makes cloud top lower in dry column

Cloud model for updraft

:entraining-detraining plume model

What we have: η, h_u, q_u^t, w_u^2

What we need: M_u, s_u, q_u, c, e

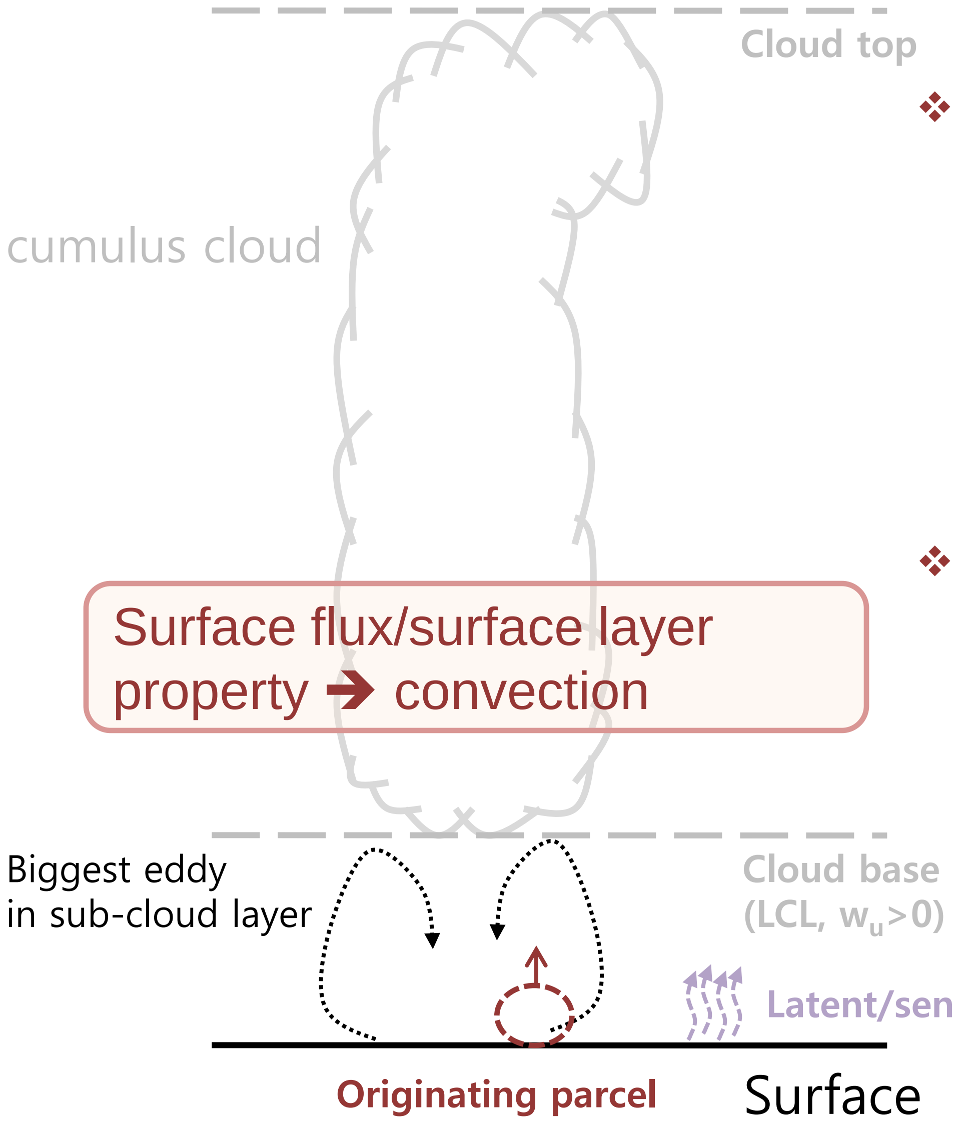
$M_u = \eta M_b$: Closure

❖ Large-scale budget equations for dry static energy and water vapor

$$\frac{\partial \bar{s}}{\partial t} + \vec{\bar{v}} \cdot \nabla \bar{s} + \bar{w}\frac{\partial \bar{s}}{\partial z} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}[M_u s_u + M_d s_d - (M_u + M_d)\bar{s}] - \frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\left(\bar{\rho}\overline{w's'}\right)_{tu} + L(\bar{c} - \bar{e}) + \overline{Q_R}$$

$$\frac{\partial \bar{q}}{\partial t} + \vec{\bar{v}} \cdot \nabla \bar{q} + \bar{w}\frac{\partial \bar{q}}{\partial z} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}[M_u q_u + M_d q_d - (M_u + M_d)\bar{q}] - \frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\left(\bar{\rho}\overline{w'q'}\right)_{tu} - (\bar{c} - \bar{e})$$

Properties of originating parcel



❖ **Initialize parcel properties**

$$w_u(z_1) = \sigma_w(z_1)$$

Surface flux

$$\phi_u(z_1) = \bar{\phi}(z_1) + b\frac{\overline{w'\phi'_s}}{\sigma_w(z_1)}$$

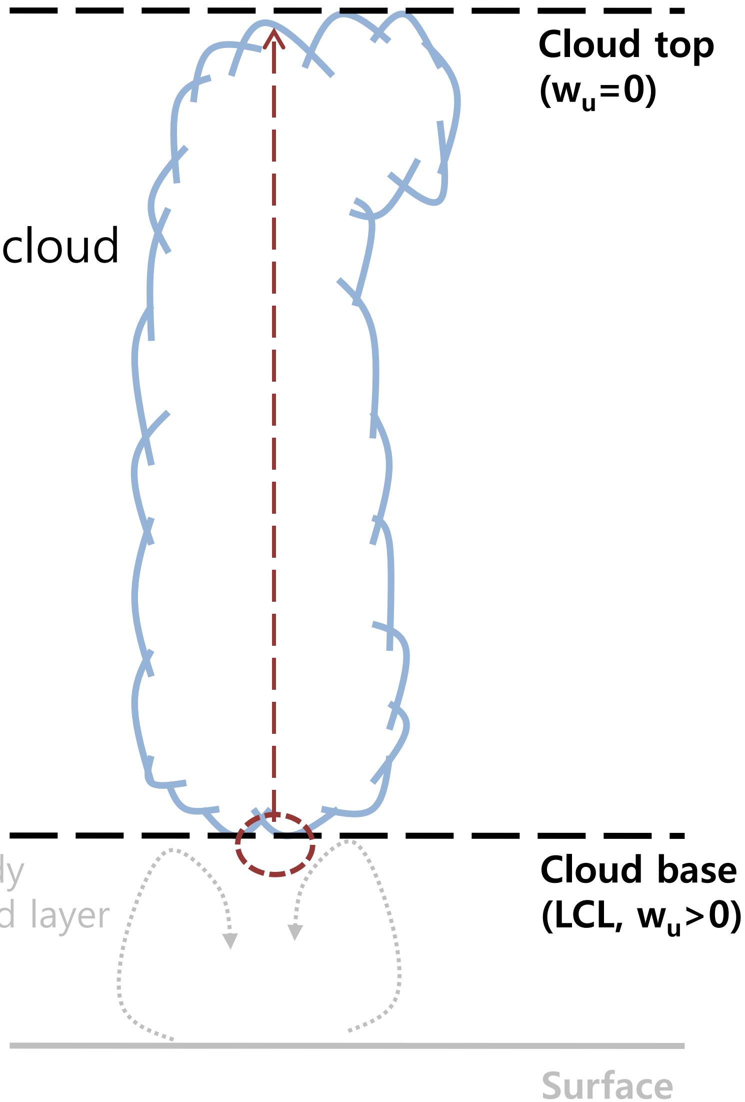
Troen and Mahrt (1986)
*b=1

❖ **Empirical expression for $\sigma_w(z_1)$**

$$\frac{\sigma_w(z_1)}{w_*} \cong 1.2\left[\left(\frac{u_*}{w_*}\right)^3 + 0.6\frac{z}{z_i}\right]^{1/3}$$

Holtslag and Meong (1986)

Cloud layer



❖ **Equations for updraft properties**

$$\frac{\partial h_u}{\partial z} = -\varepsilon\left(h_u - \bar{h}\right)$$

$$\frac{\partial q_u^t}{\partial z} = -\varepsilon(q_u^t - \bar{q}^t) - g_p$$

$$\frac{1}{2}\frac{\partial w_u^2}{\partial z} = aB_u - b\varepsilon w_u^2$$

*a=1/6, b=2

❖ **Entrainment rate (cloud layer)**

$$\varepsilon = \frac{C_\varepsilon a}{{w_u}^2} B_u$$

Gregory (2001)

$$C_\varepsilon = \left(\frac{1}{\overline{\overline{RH}}} - 1\right)$$