# Overview of Physical Parameterizations

Song-You Hong

(KIAPS: Korea Institute of Atmospheric Prediction Systems)

(Also, an NCAR affiliate scientist)

1) Concept
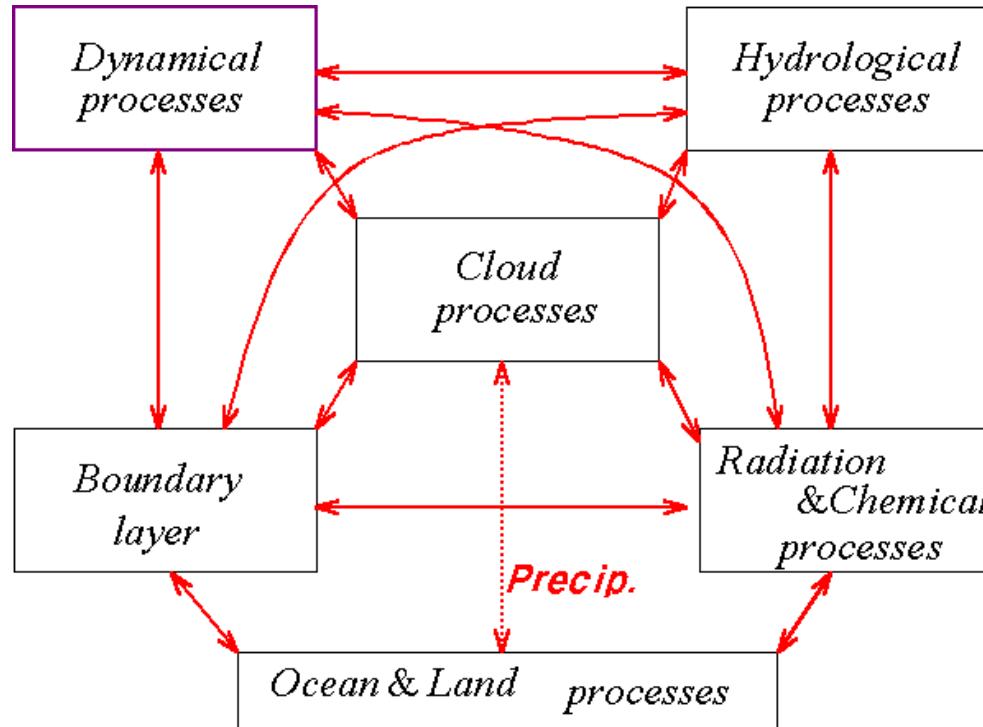
* **Physical processes in the atmosphere**
 : Specification of heating, moistening and frictional terms in terms of dependent
   variables of prediction model
 → Each process is a specialized branch of atmospheric sciences.

* **Parameterization**

The formulation of physical process in terms of the model variables as parameters,
 i.e., constants or functional relations.

2

1) Concept…continued

Subgrid scale process

Any numerical model of the atmosphere must use a finite resolution in representing continuum certain physical & dynamical phenomena that are smaller than computational grid.

- Subgrid process (Energy perspective)


small amount of E

GCM Grid cell 40-400km
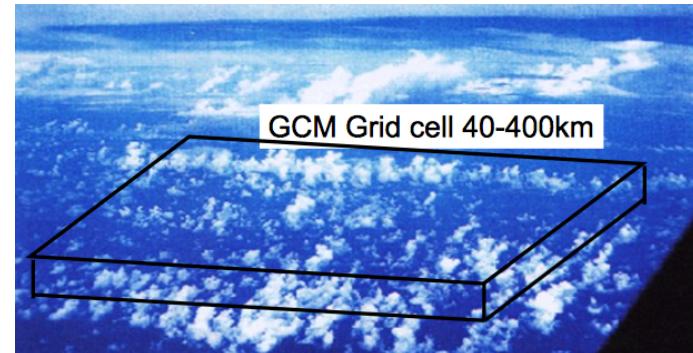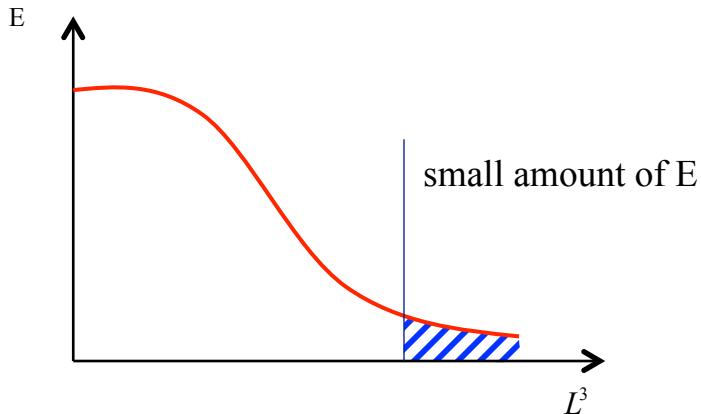
$\Delta x \to 0$, the energy dissipation takes place by molecular viscosity

Objective of subgrid-scale parameterization

"To design the physical formulation of energy sink, withdrawing the equivalent amount of energy comparable to cascading energy down at the grid scale in an ideal situation."

3

1) Concept…continued

※ Parameterization that are only somewhat smaller than the smallest
   resolved scales.

E ↑

Model

1000   100   ⬆ $L\,(km)$

NWP model   → Parameterization

←increasing scale   ← hard truncation limit
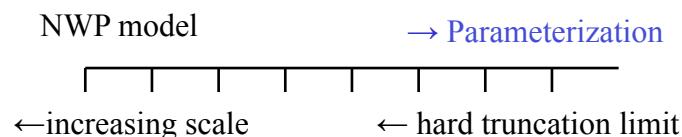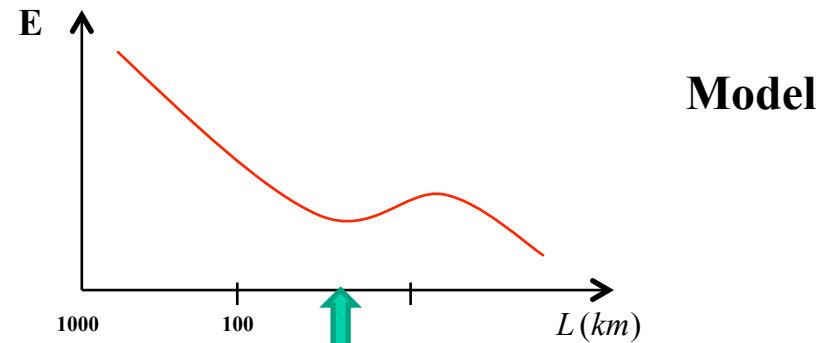
where truncation limit ; spectral gap

Unfortunately, there is no spectral gap

E ↑

Nature

1000   100   ⬆   10   1 $L\,(km)$

4
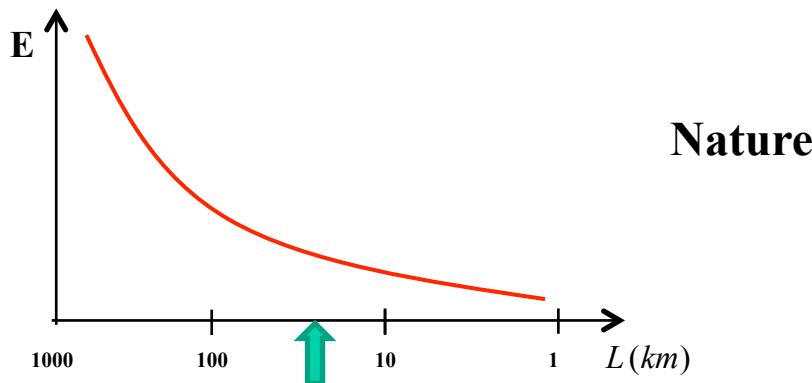
2) Subgrid scale process & Reynolds averaging

Consider prognostic water vapor equation

$$\frac{\partial \rho q}{\partial t} = -\frac{\partial \rho u q}{\partial x} - \frac{\partial \rho v q}{\partial y} - \frac{\partial \rho w q}{\partial z} + \rho E - \rho C \qquad \cdots (1)$$

In the real atmosphere,

$$u = \bar{u} + u', \qquad q = \bar{q} + q' \qquad \left(\begin{array}{l} \ast \bar{a} : grid -resolvable \\ \quad a' : subgrid \ \ scale \ \ perturbation \end{array} \right)$$

ρ' is neglected
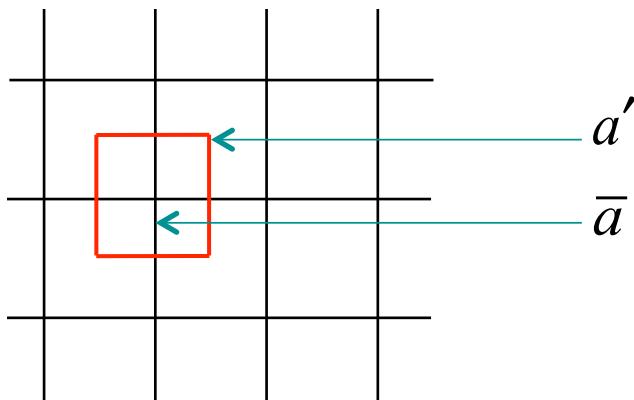
2) Subgrid scale process & Reynolds averaging…continued

* Rule of Reynolds average : $\quad \overline{q'} = 0, \ \overline{u'\overline{q}} = 0, \ \overline{\overline{u}\,\overline{q}} = \overline{u}\,\overline{q}$

then eq.(1) becomes

$$\frac{\partial \rho \overline{q}}{\partial t} = -\frac{\partial \overline{\rho u \overline{q}}}{\partial x} - \frac{\partial \overline{\rho v \overline{q}}}{\partial y} - \frac{\partial \overline{\rho w \overline{q}}}{\partial z} - \frac{\partial \overline{\rho u'q'}}{\partial x} - \frac{\partial \overline{\rho v'q'}}{\partial y} - \frac{\partial \overline{\rho w'q'}}{\partial z} + \rho E - \rho C \ \cdots (2)$$

        ①   ②

    ① grid-resolvable advection (dynamical process)
    ② turbulent transport

* How to parameterize the effect of turbulent transport

a) $\ -\rho \overline{w'q'} = 0$:   0th order closure

b) $\ -\rho \overline{w'q'} = K \dfrac{\partial \overline{q}}{\partial z}$:   1st order closure   (K-theory)

c) obtain a prognostic equation for $\overline{w'q'}$ from (1), (2)

$$\frac{\partial \rho w q}{\partial t} = -\frac{\partial \rho u w q}{\partial x} + \cdots$$

taking Reynolds averaging,

$$\frac{\partial \overline{\rho w'q'}}{\partial t} = \frac{\partial \overline{\rho w'w'q'}}{\partial z}$$

$$-\rho \overline{w'w'q'} = K' \frac{\partial \overline{\rho w'q'}}{\partial z} \qquad : \text{2nd order closure}$$

3) Schematic of physics algorithm : In modeled atmosphere : 7* (essential) ~10

$$\frac{d\ln\theta}{dt} = \frac{H}{c_p T} \quad , \quad \frac{dq}{dt} = S, \quad \frac{d\vec{u}}{dt} = \nabla_z \vec{\tau}$$

GWDC

tropopause

GWDO

* Radiation

MPS: Microphysics rain*

CPS: Convection rain*

* Vertical diffusion

GWDO

shallow convection

(PBL)

PBL*

σ= 1

SFC layer*

Soil Model*
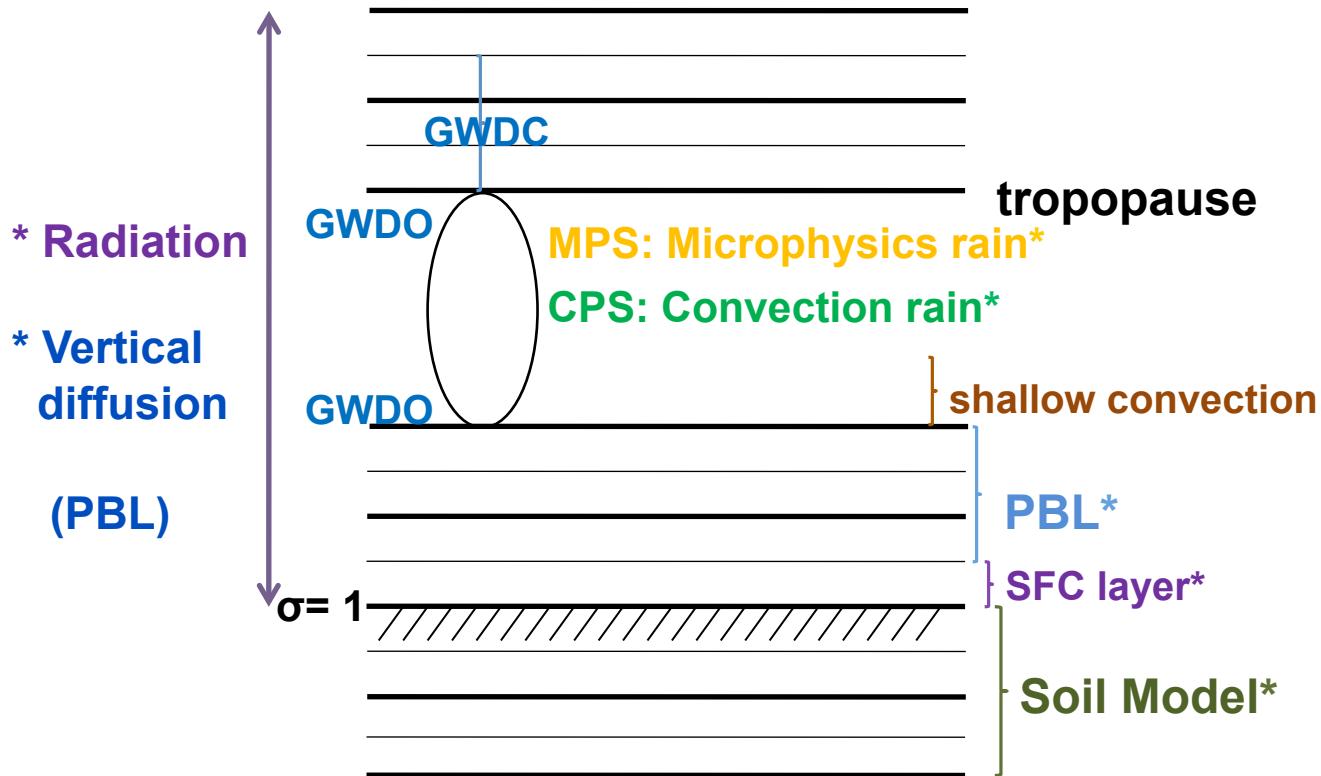
1. Radiation

1.1 Concept
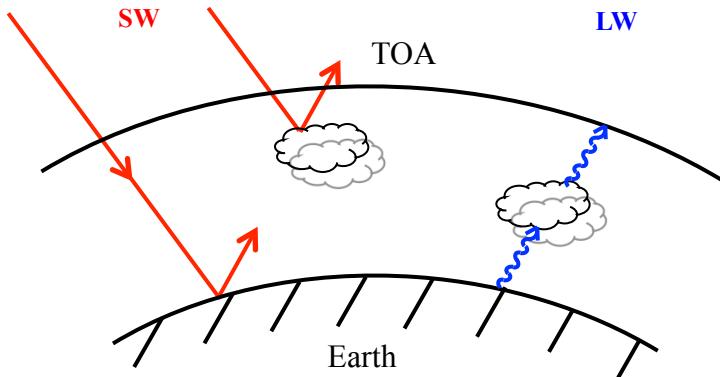
TOA (top of the atmos) : S = 1360 Wm^{-2}

Mean Flux : $\dfrac{S}{4}$ = 340 Wm^{-2} → Energy source for Earth

30% : reflected from the atmosphere clouds

→ Back to space by terrestrial infrared radiation

$\left\{\begin{array}{l} 25\% : \text{absorbed in the atmosphere} \\ 45\% : \text{absorbed at the earth surface} \end{array}\right\}$

Energy loss

Energy gain

Energy loss
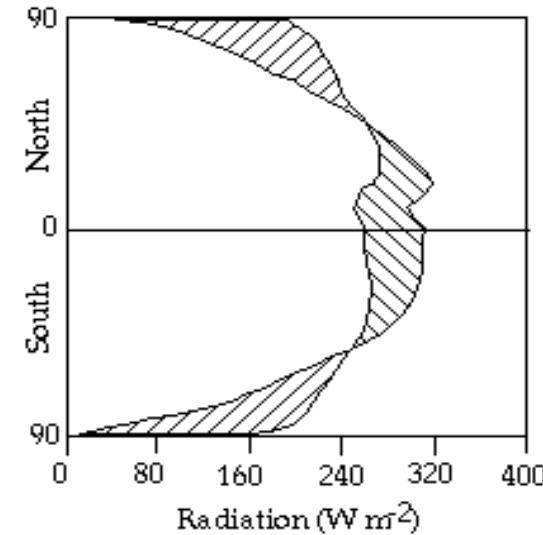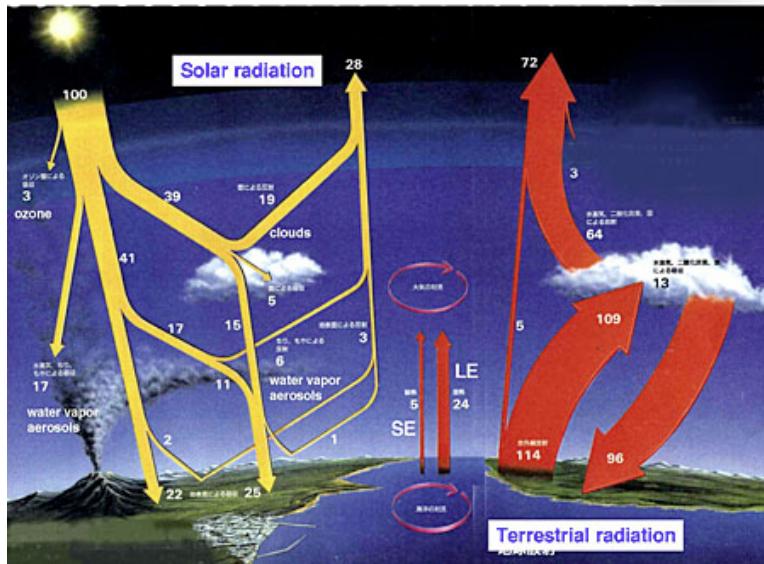
1.2 Solar radiative transfer

I (Insolation)

TOA

sfc

$0.5 \mu m$ λ (wave length)

h = elevation angle, measured up from horizon   z = zenith angle, measured from vertical   A = Azimuth angle, measured clockwise from North
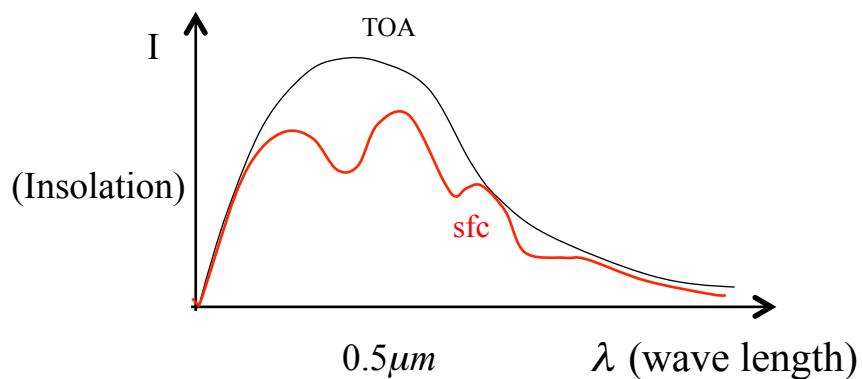
- At TOA,

$$F = S(\frac{dm}{d})^2 \cos\theta_0 \qquad (\theta_0 : \text{Zenith angle})$$

- Basic equations $\mu = \cos\theta$

$$\mu \frac{dI(\tau,\mu,\phi)}{d\tau} = I(\tau,\mu,\phi) - J(\tau,\mu,\phi)$$

absorption   source emission

$$d\tau = -k_\nu \rho_a dz \qquad \tau(\text{optical depth}) = \int_z^{z_\infty} k_\nu(z')\rho_a(z')dz' = \int_0^p k_\nu(p')q(p')\frac{dp'}{g}$$

9
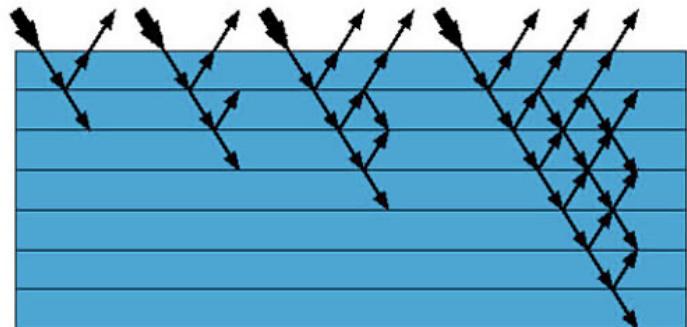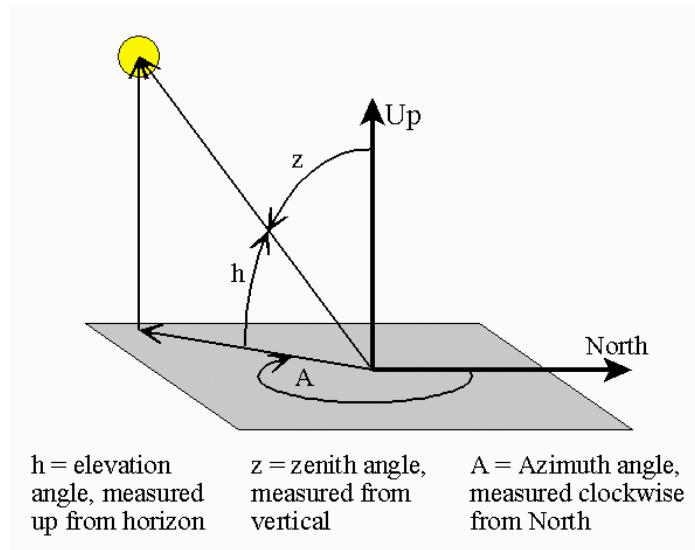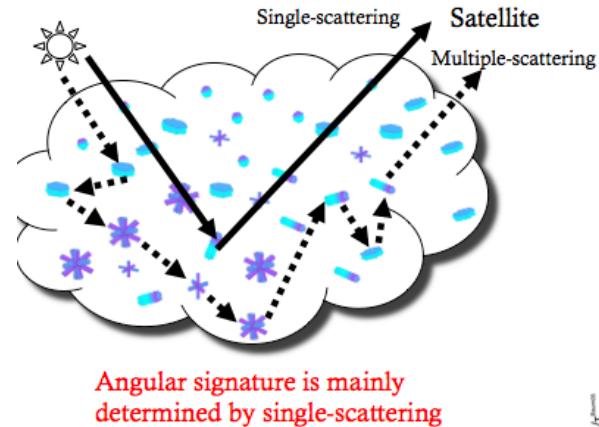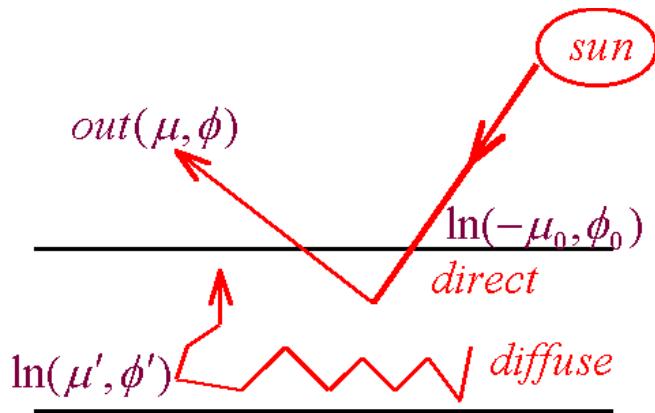
$$J = J(\tau,\mu,\phi) = \frac{\tilde{\omega}}{4\pi} \int_0^{2\pi} \int_{-1}^{1} I(\tau,\mu',\phi')P(\mu,\phi;\mu',\phi')d\mu'd\phi' \text{[diffuse (multiple) scattering]}$$

$$+ \frac{\tilde{\omega}}{4\pi} F_0 P(\mu,\phi;-\mu_0,\phi_0)e^{-\frac{\tau}{\mu_0}} \text{[single(direct) scattering]}$$

$$\begin{cases} P : \text{Scattering phase function :redirects} \quad (\mu',\phi') \; (\mu,\phi) \\ \tilde{\omega} = \dfrac{\sigma_s}{\sigma_e} : \text{Scatteing albedo} \\ \qquad \text{scattering cross section/extinction(scattering + absorption) cross section} \end{cases}$$

* remove ϕ dependency using $P(\cos\theta)$ function

* $P, \tilde{\omega}$, Albedo depend on λ, particle size & shape.

$$P(\cos\phi) = \sum_{l=0}^{N} \tilde{\omega}_l P_l(\cos\phi) \quad : \text{Legendre Polynomial}$$

10

$$F_{\lambda_0}\cos\theta_0$$

$$\theta_0 \quad F_{\lambda_0}$$

$$0 \qquad\qquad \infty(u_1)$$

$$F_\lambda^-(z+\Delta z) \quad F_\lambda^\pm(z+\Delta z)$$

$$P-\Delta P \qquad\qquad z+\Delta z(u+\Delta u)$$

$$P \qquad\qquad z(u)$$

$$F_\lambda^-(z) \quad F_\lambda^\pm(z)$$

$$P_s \qquad\qquad 0\ (0)$$
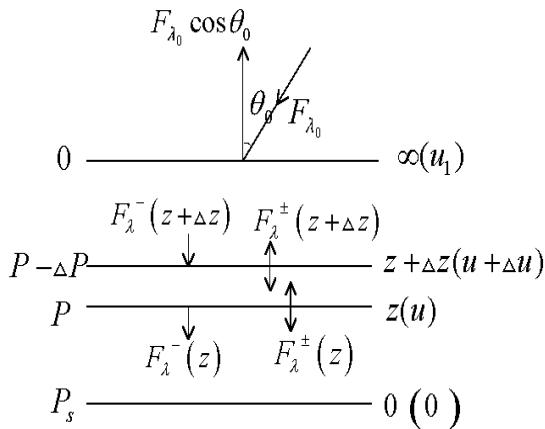
Radiative transfer equation solver.

$$\rightarrow\ \begin{cases} \text{Discrete - ordinates method} \\ \text{Two - Stream and Eddington's approximation} \\ \text{Delta - function adjustment and similarity principle} \\ \delta \text{ - Four stream approximation} \end{cases}$$

1.3 Terrestrial radiation

$$0 \qquad\qquad \infty(u_1)$$

$$P-\Delta P \quad\dfrac{F(z+\Delta z)}{} \qquad z+\Delta z(u+\Delta u)$$

$$P \quad\dfrac{F(z)}{} \qquad z(u)$$

$$P_s \qquad\qquad 0$$
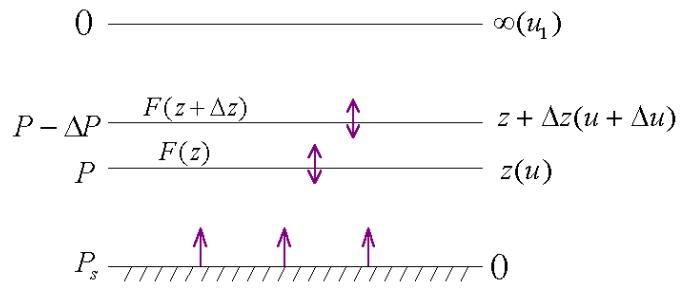
$$0,\mu \qquad\qquad \tau_\infty, z_\infty, 0$$

$$\tau',\mu' \qquad\qquad \tau', z', P'$$

$$\tau,\mu \qquad\qquad \tau, z, P$$

$$\tau',\mu' \qquad\qquad \tau', z', P'$$

$$\tau, 0 \qquad\qquad \tau_s, 0, P_*$$

$$F(z) = F^\uparrow(z) - F^\downarrow(z)$$

$$\Delta F = F(z+\Delta z) - F(z)$$

$$\left.\frac{\partial T}{\partial t}\right|_{IR} = -\frac{1}{c_P\rho}\frac{\Delta F}{\Delta P} = -\frac{g}{c_P}\frac{\Delta F}{\Delta u}$$
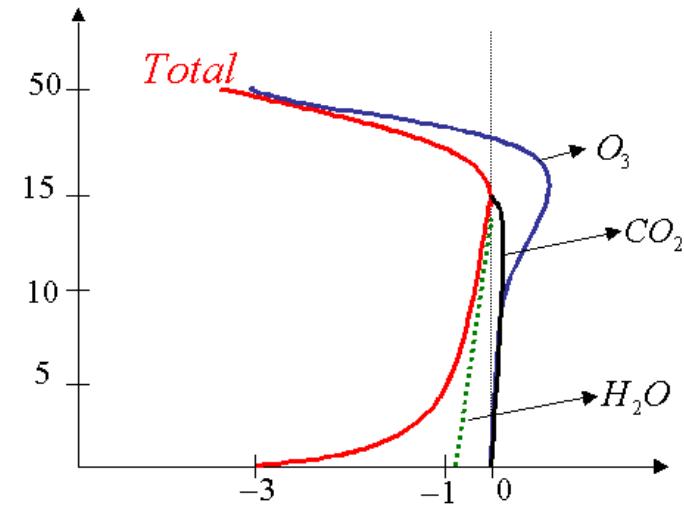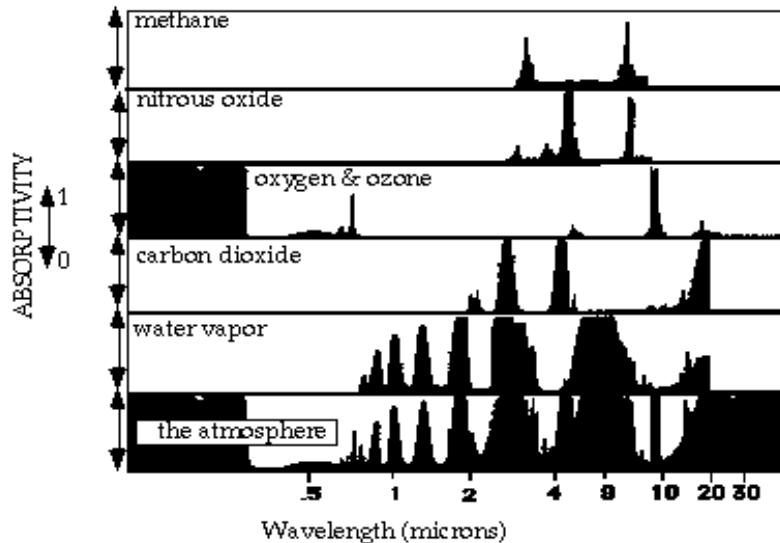
In spectral bands (monochromatic)

$\uparrow \quad \mu \dfrac{dI_\nu(\tau,\mu)}{d\tau} = I_\nu(\tau,\mu) - B_\nu(T)$

$\downarrow \quad -\mu \dfrac{dI_\nu(\tau,-\mu)}{d\tau} = I_\nu(\tau,-\mu) - B_\nu(T)$

B.C. $\begin{cases} SFC\ (\tau=\tau_1),\ I_\nu(\tau,\mu)=B_\nu(T_s) \\ TOP\ (\tau=0),\ I_\nu(0,-\mu)=0 \end{cases}$

$F^{\uparrow}(\tau) = 2\pi B_\nu(T_s)\int_0^1 e^{-\frac{(\tau_1-\tau)}{\mu}}\mu\, d\mu + 2\int_0^1\int_\tau^{\tau_1} \pi B_\nu[T(\tau')]e^{-\frac{(\tau'-\tau)}{\mu}}\, d\tau' d\mu$

$F^{\downarrow}(\tau) = 2\int_0^1\int_0^\tau \pi B_\nu[T(\tau')]e^{-\frac{(\tau-\tau')}{\mu}}\, d\tau' d\mu$

$d\tau = -k_\nu \rho\, dz, \quad u_1 = \int_0^\infty \rho\, dz$ (path length)
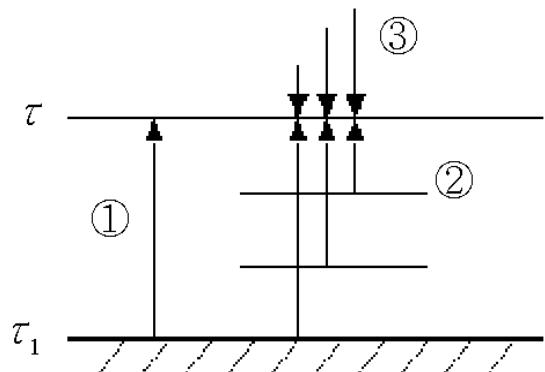
LW is time consuming !

12

1.4 Cloud fraction

## i) Conventional method (Slingo)

$f = f_c(\text{convective cloud, CPS}) + f_l(\text{large-scale cloud, MPS})$

f_c : depends on precipitation, $p_{top},\ p_{bottom}$

f_l : depends on RH $= 1 - \left[\dfrac{1-RH}{1-RH_0} \right]^{0.5}$

where RH_0 is the critical value of RH,

which is optimized based on observations
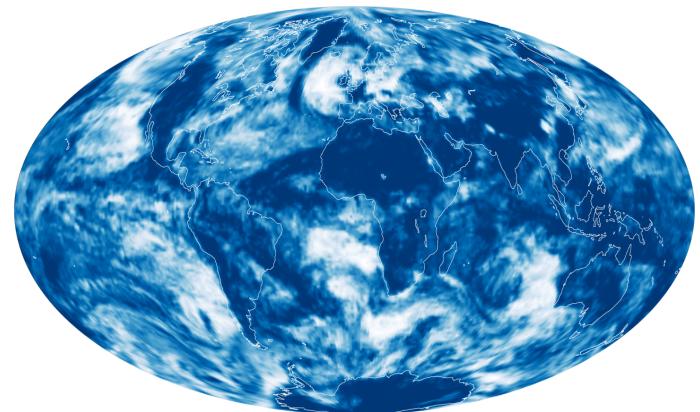
ii) Advanced method (Chou)
- inclusion of ice, liquid hydrometeors as prognostic water substances
- consistent treatment of water substance for both precipitation & radiative properties.

f_c : uses information of detrained water substances from sub-grid scale clouds in convective parameterization scheme (CPS)

$\leftarrow \qquad \rightarrow$ detrained

$u_{q_c}, u_{q_l}, k_{q_c}, k_{q_l}$
in radiation code
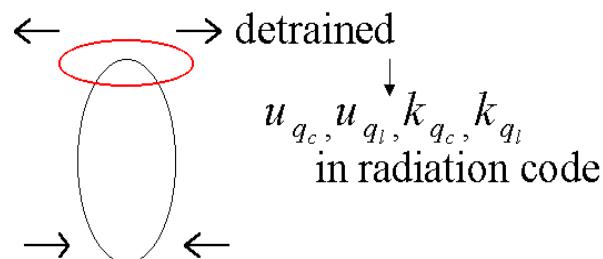
f_l use the hydrometeor information from microphysics routine (MPS), $q_c, q_s, q_i, \cdots$

13

iii) Radiation properties

$\tau_i^c = cwp\,[a_i + \dfrac{b_i}{r_{ei}}]\,f_{ice}$ (optical thickness)

$w_i^c = 1 - c_i - d_i\, r_{ei}$ (co-albedo)

$g_i^c = e_i - f_i\, r_{ei}$ (asymmetry factor)

$f_i^c = (g_i)^2$ (forward peak fraction)

  a-f : coeff : depends upon band and k-

$$\overline{\tau_c} = \sum_i \tau_i \qquad\qquad i : \text{each gas}$$

(The effective optical thickness for each spectral band)

- The long wave cloud emissivity (E_{cld})

$$c_f' = E_{cld} c_f$$

$$E_{cld} = 1 - e^{-Dk_{abc}cwp}$$

where $D = 1.66$: diffusivity factor

$k_{abc} = k_l(1 - f_{ice}) + k_i f_{ice}$: absorptivity coefficient

## - For diagnostic microphysics scheme,

- cloud water scale height   - cloud droplet size,   – ice fraction, f_{ice}

$h_1 = a\ln(1.0 + \dfrac{b}{g}\displaystyle\int_{P_T}^{P_S} q\,dp)$ $r_{ee}\begin{cases} =10\mu m & \text{over ocean} \\ <10\mu m & \text{over land} \end{cases}$: warm clouds

r_{ei}: $10\mu m$ (low) $\sim$ $30\mu m$: (high) ice clouds
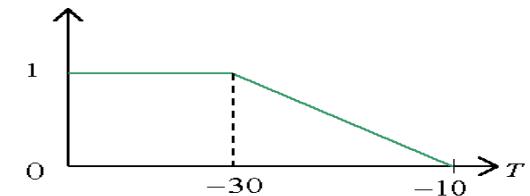
- For prognostic microphysics scheme,

  : Broadband radiation : Radiative properties are explicitly computed from prognostic water substances

  : Simplified radiation : Dudhia (1989)

α_p (absorption coefficient) $= \dfrac{1.66}{2000}(\dfrac{\pi N_0}{\rho_{rs}^3})^{\frac{1}{4}}$ $m^2 g^{-1} = \begin{bmatrix} 2.34\times10^{-3} & m^2 g^{-1} \text{ for snow} \\ 0.33\times10^{-3} & m^2 g^{-1} \text{ for rain} \end{bmatrix}$

u_p (effective water path length) $= (\rho q_{rs})^{\frac{3}{4}}\Delta z \times 1000$ gm^{-2} $\to \tau_p$ (transmission) $= \exp(-\alpha_p u_p)$

14

iv) Cloud overlapping
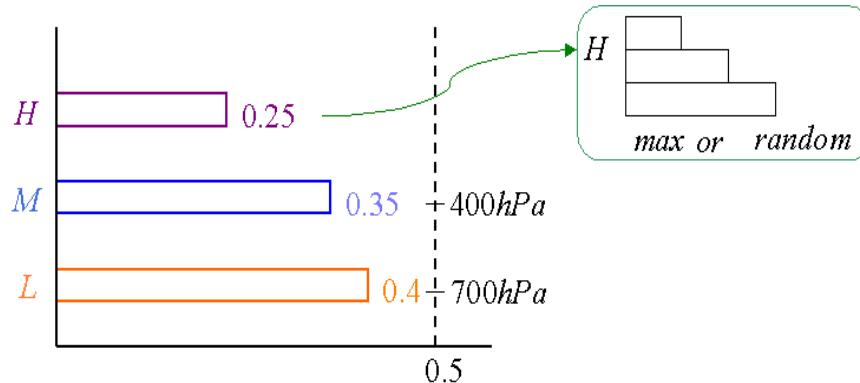
Maximum overlapping : 0.4
Minimum overlapping : 1.0
Random overlapping : $H + (1-H)M + \{1 - H - (1-H)M\}L = 0.6$

- Computation :

τ is scaled by A_c (cloud cover) at a given layer.

A_{free} A_{cld}

- Flux for each of $A_c, (1 - A_c) \rightarrow$ summation

- Issues : $A_c = 0$ or 1 ⬅ in WRF   versus partial cloudiness in GFS   : WRF has partial cloudiness recently

- Interaction :   Radiation   *reflect SW, LW*   Cloud

enhance or reduce cloud activity

15
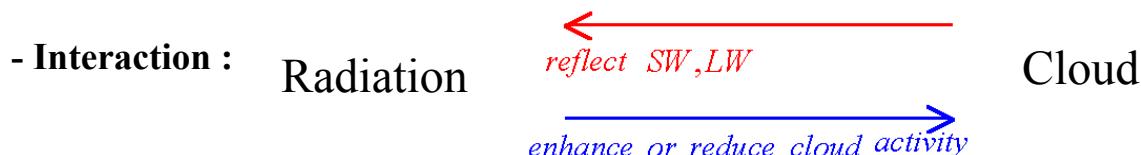
2. Land-surface processes

2.1 Concept : Surface layer + soil model
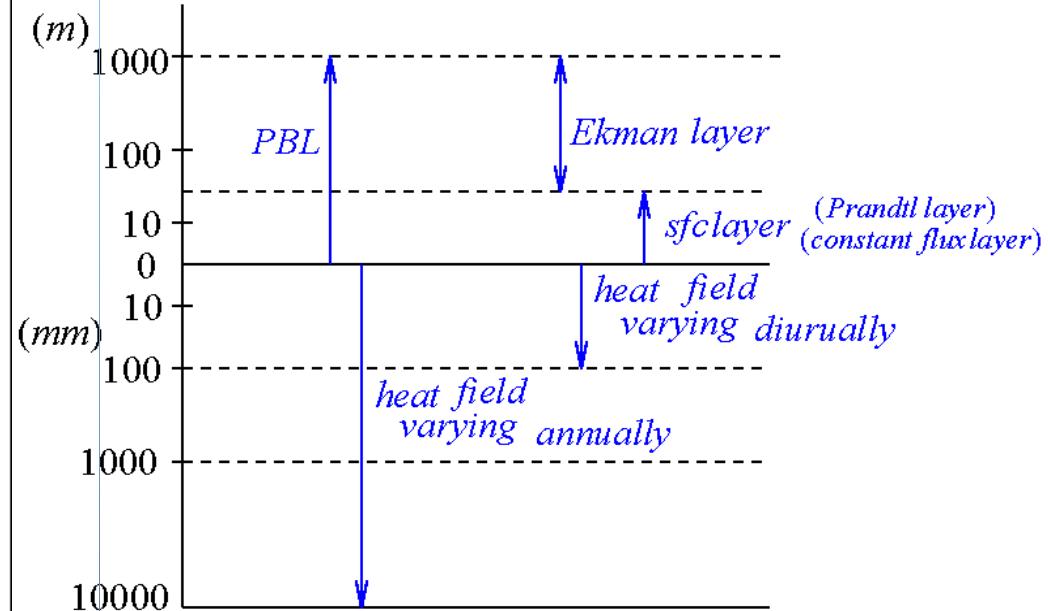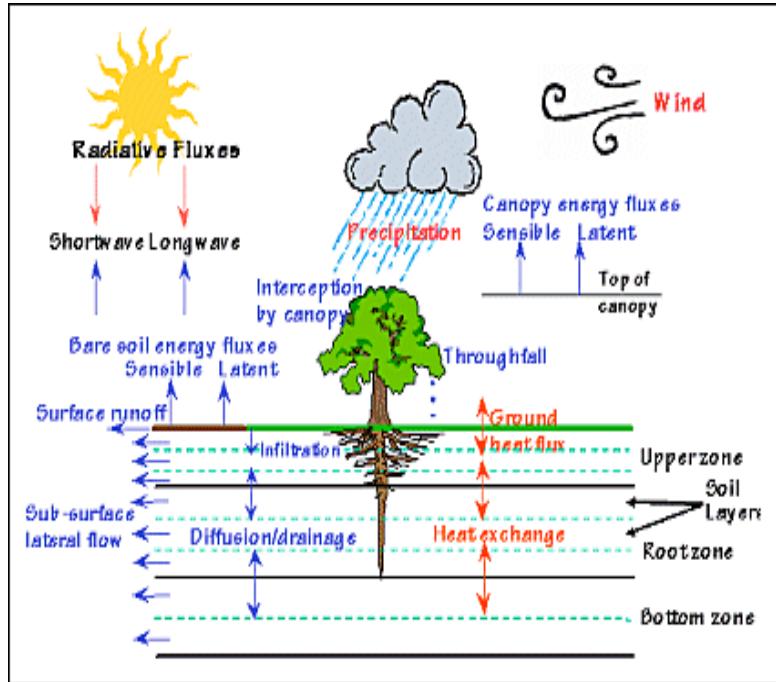
Atmospheric surface layer : the lowest part of the atmospheric boundary layer (typically about a tenth of the height of the BL) where mechanical (shear) generation of turbulence exceeds buoyant generation or consumption. Turbulent fluxes and stress are nearly constant with height.

➔ **In atmospheric models**, it is defined the height of the lowest model level.

2.2 Surface layer parameterization

Surface layer schemes calculate friction velocities and exchange coefficients that enable the calculation of surface heat and moisture fluxes by the land-surface models. These fluxes provide a lower boundary condition for the vertical transport done in the PBL Schemes.

Over water surfaces, the surface fluxes and surface diagnostic fields are computed in the surface layer scheme itself. Sea surface temperature can be predicted by the surface energy budget and mixed layer mixing

1) Bulk method (before 1990, MM4)

$$H_0 = \rho C_p C_H |\vec{V}_a| \Delta T$$

$$E_0 = \rho L C_H |\vec{V}_a| \Delta q M_a$$

$$\vec{\tau}_0 = \rho C_D |V_a| \vec{V}_a$$

C_D, C_H : prescribed

   = 0.01 over land, = 0.001 over water

2) Monin-Obukov similarity

$$\frac{k_z}{u_*}\frac{\partial u}{\partial z} = \phi_m(z/L), \quad \frac{k_z}{u_*}\frac{\partial \theta}{\partial z} = \phi_t(z/L)$$

Integrate, $\quad F_m = \int_{z_0}^{h_s} \frac{dz}{z}\phi_m dz = \ln(\frac{h_s}{z_0}) - \psi_m(h_s, z_0, L)$

$\ln z$ — *stable* — *adiabatic* — *unstable* — z_0 — $\bar{u}$

$$\vec{u} = C_u[\ln\frac{z}{z_0} + \Phi]$$

Φ : curving factor
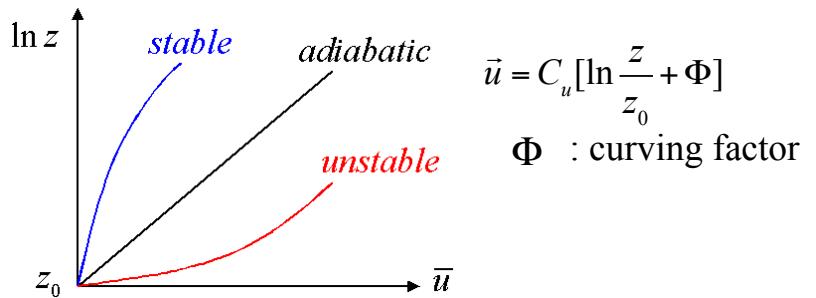
※ **Profile function** : ϕ_m and ϕ_t

Dyer and Hicks formula for similarity

- unstable (L < 0)

$$\phi_m = (1-16\frac{0.1h}{L})^{-\frac{1}{4}} \quad \text{for } u, v$$

$$\phi_t = (1-16\frac{0.1h}{L})^{-\frac{1}{2}} \quad \text{for } \theta, q$$

- stable (L > 0)

$$\phi_m = \phi_t = (1+5\frac{0.1h}{L})$$

where $L = u_*^2\bar{\theta}/(kg\theta_*) = -\dfrac{\rho C_p \theta_0 u_*^3}{kgH_0}$

Kantha (2003)

$$\frac{h_s}{L} = \frac{\phi_m^2(hs/L)}{\phi_t(hs/L)} Ri = \zeta \ \text{(Zeta=hs/L)}$$

where $Ri = \dfrac{g}{\theta}\dfrac{\partial\theta}{\partial z}(\dfrac{\partial u}{\partial z})^{-2}$

※ **Useful relation** :

Given the F_m, F_H $C_D = k^2/F_m^2, C_Q = C_H = k^2/(F_mF_t)$ $u_* = kU/F_m$

$$\tau_0 = \rho k_m \frac{du}{dz} = -\overline{u'w'} = \rho C_d U^2$$

$$H_0 = -\rho C_p k_h \frac{d\theta}{dz} = \rho C_p \overline{\theta'w'} = -\rho C_p C_H U\Delta\theta$$

$$E_0 = -\rho L\overline{q'w'} = -\rho L C_q U\Delta q$$

18

2.3 Soil model

1) **Slab model :** force-restore method (before 1990 : MM4)

$$\frac{\partial T_s}{\partial t} = \lambda_T(R_n - LE - H) - \frac{2\pi}{\tau}(T_s - T_a)$$

$$\frac{\partial T_s}{\partial t} = \frac{1}{\tau}(T_s - T_m) \quad : \textbf{\textit{T}}_{\textbf{\textit{m}}}\textbf{, daily mean}$$

K
K+1/2 — T_a
K+1
GROUND T_s
SUBSTRATE T_m
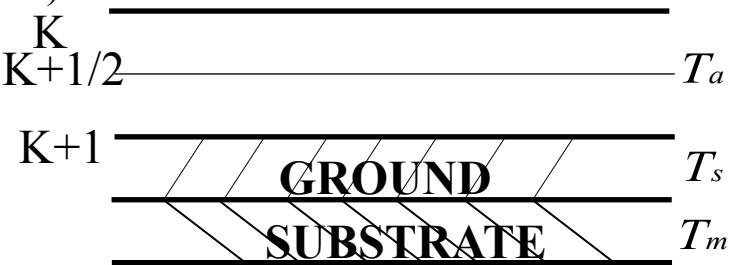
2) **Multi-layer model** : OSU method

$$\frac{\partial T_s}{\partial t} = \lambda_T(R_n - LE - H) \qquad : \textbf{surface T}$$

$$(\rho C)_i \frac{\partial T_g}{\partial t} = \frac{\partial}{\partial z}(\lambda T_g \frac{\partial T_g}{\partial z}) \quad : \textbf{soil T}$$

$$\frac{\partial \Theta}{\partial t} = \frac{\partial}{\partial z}(D \frac{\partial \Theta}{\partial z}) + K \frac{\partial \Theta}{\partial z} + F_\Theta \quad : \textbf{soil moisture}$$

- NOAH, SIB, PLACE, VIC, CLM, etc

RA analysis: 2-layer soil model

19
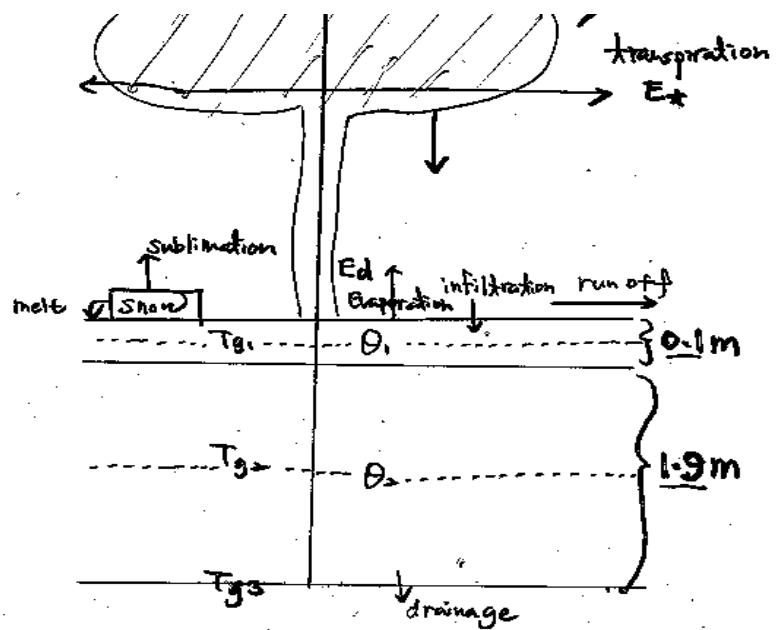
2.4 Vegetation type → z_0, Albedo

Vegetation types

MODIS (satellite)

- evergreen needleleaf forest
- evergreen broadleaf forest
- deciduous needleleaf forest
- deciduous broadleaf forest
- mixed forest
- closed shrubs
- open shrubs
- woody savanna
- savanna
- grasslands
- permanent wetlands
- croplands
- urban and built-up
- crop/natural vegetation mosaic
- permanent snow/ice
- barren or sparse
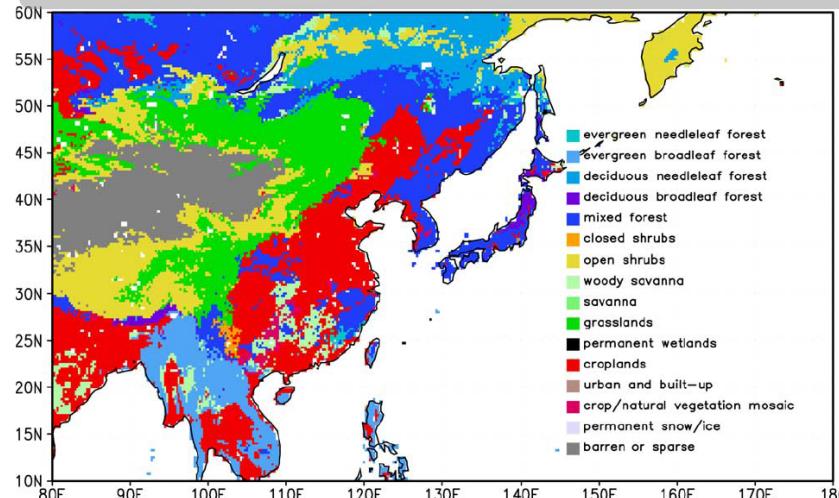
13 type data set
1 degree

12 type data set
20 min

The Simple Biosphere model (SiB)

United States Geological Survey's (USGS)

quite broad desert region

- tropical rainforest
- broadleaf deciduous tree
- mixed tree
- needleleaf evergreen tree
- needleleaf deciduous tree
- savanna
- ground cover only (perenial)
- broadleaf shrub with grnd cvr
- broadleaf shrub with baresoil
- dwarf & tundra
- bare soil
- crops

- mixed farming tall grass
- tall/med grass, shrub
- short grass meadow, shrub
- tundra
- sandy desert
- rocky desert
- tropical evergreen forest
- needleleaf evergreen forest
- medium grass, woods
- deciduous forest
- mixed forest
- ice

20

Albedo and roughness length (z_0)

| **Sib** | **USGS** | **USGS-Sib** |

Albedo

16.6 %♪ · 25.5 % · desert · different type
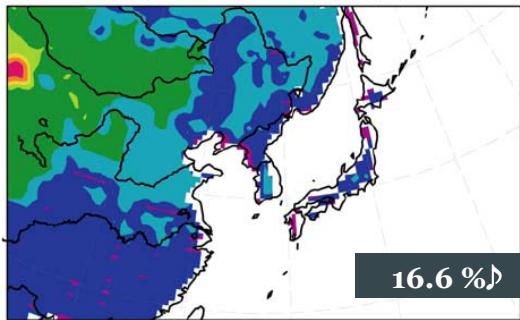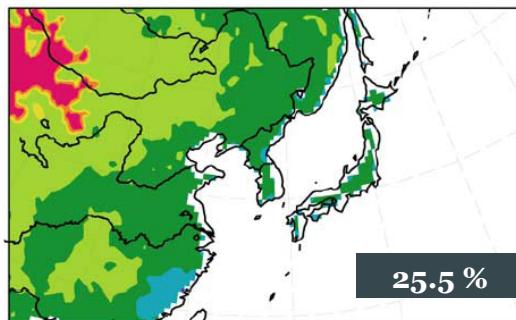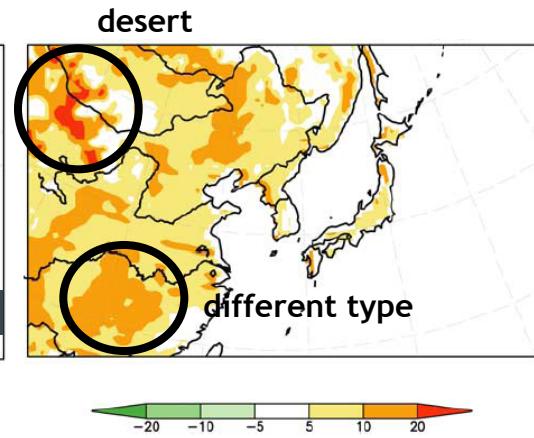
Roughness length
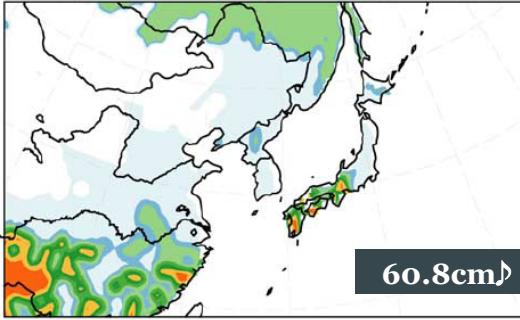
60.8cm♪ · 38.0cm♪
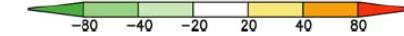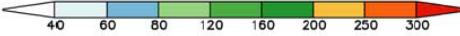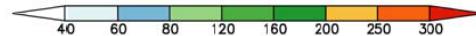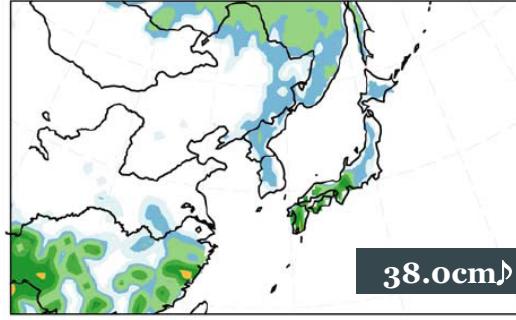
Much uncertainties in calibration/optimization !!!

21

3. Vertical diffusion (PBL)

3.1 Concept

- computes the parameterized effects of vertical turbulent eddy diffusion of momentum, water vapor and sensible heat fluxes

Structure of Planetary Boundary Layer
adapted from Stull, 1988.
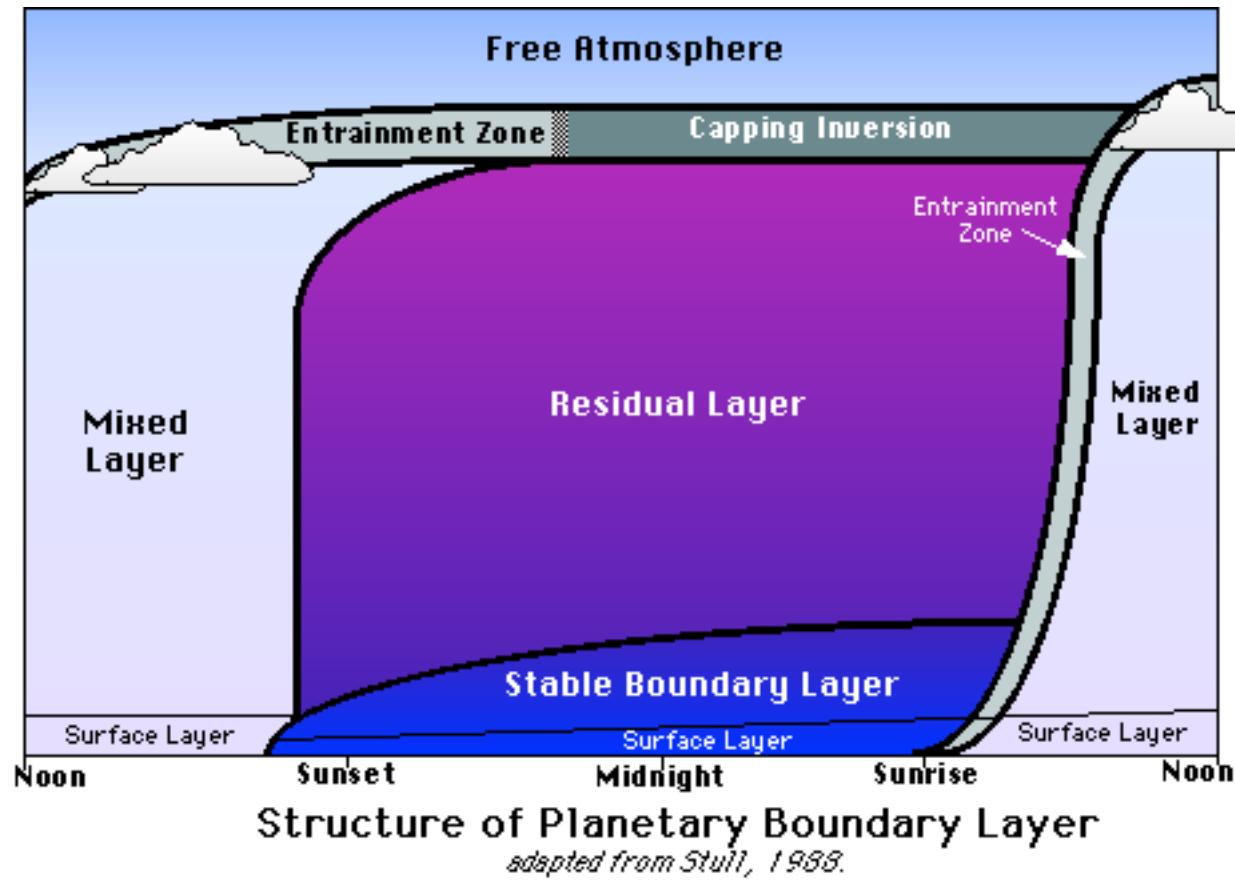
3.2 Planetary Boundary Layer Structure : schematic

Daytime profiles

Daytime flux profiles

Nighttime flux profiles
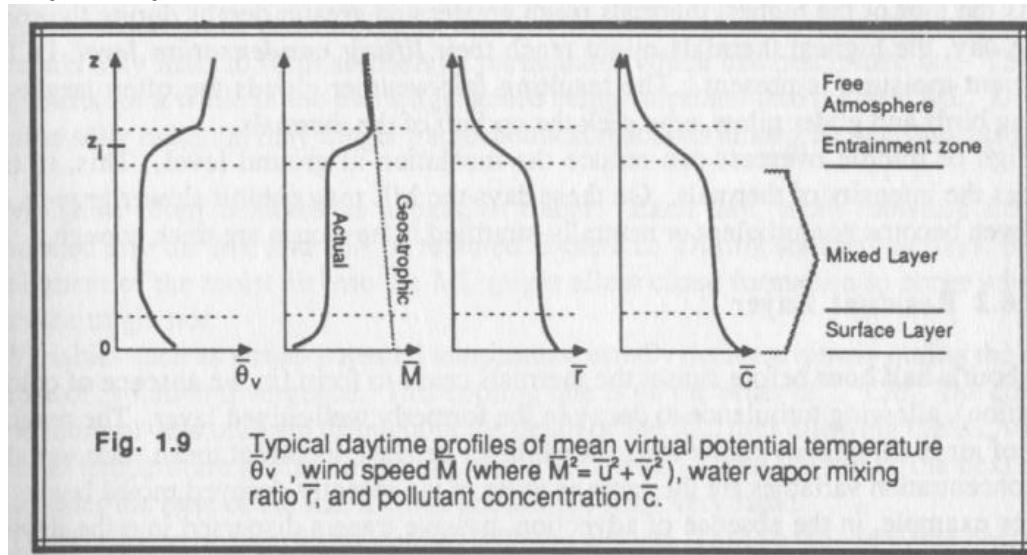
Fig. 1.9 Typical daytime profiles of mean virtual potential temperature $\overline{\theta}_v$, wind speed $\overline{M}$ (where $\overline{M}^2 = \overline{u}^2 + \overline{v}^2$), water vapor mixing ratio $\overline{r}$, and pollutant concentration $\overline{c}$.
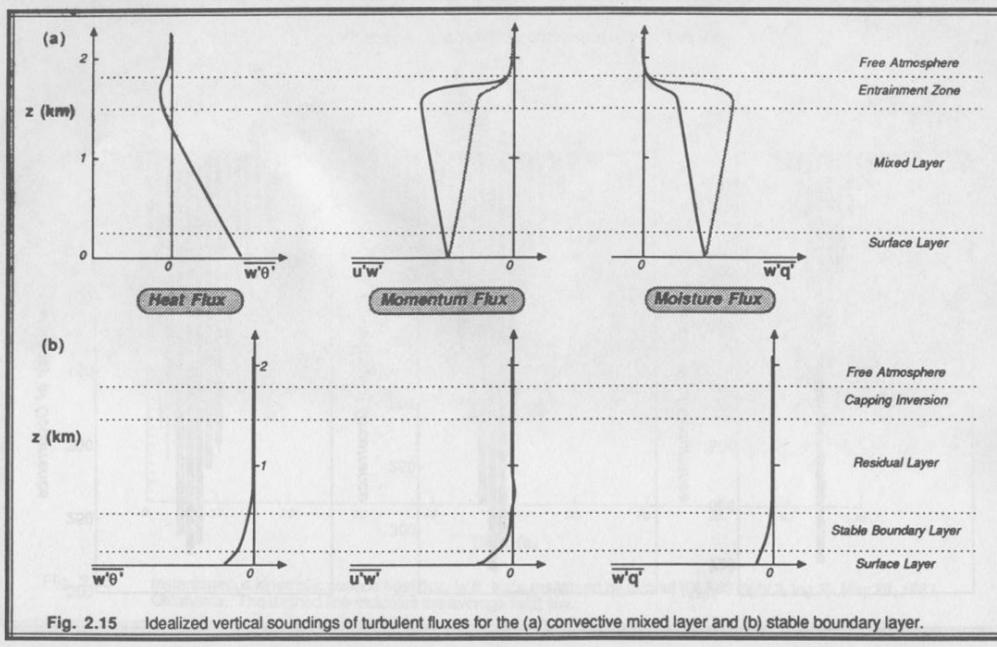
Fig. 2.15 Idealized vertical soundings of turbulent fluxes for the (a) convective mixed layer and (b) stable boundary layer.

Stull (1988)

3.3 Classifications : how to determine, k_c

i) Local diffusion (Louis 1979)

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial z}(-\overline{wc}) = \frac{\partial}{\partial z}(k_c \frac{\partial c}{\partial z}) \quad k_c : \text{ diffusivity}, \quad k_m, k_t = l^2 f_{m,t}(Ri)\left|\frac{\partial U}{\partial z}\right|$$

Local Richardson number

ii) Nonlocal diffusion (Troen and Mahrt 1986)

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial z}(-\overline{wc}) = \frac{\partial}{\partial z}(k_c(\frac{\partial c}{\partial z} - \gamma_c))$$

$$k_{zm} = kw_s z(1-\frac{z}{h})^p, \; h = R_{ibcr}\frac{\theta_m}{g}\frac{U^2(h)}{(\theta_v(h)-\theta_s)}$$

$$\theta_s = \theta_{va} + \theta_T \; (= b\frac{\overline{(\theta_v'w')}_0}{w_s}), \; w_s = u_* \phi_m^{-1}$$
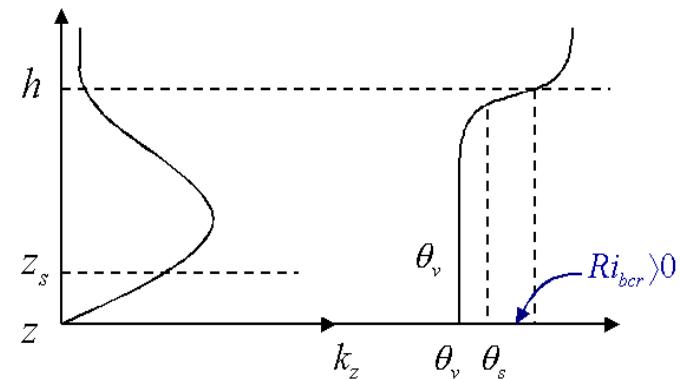
iii) Eddy mass-flux diffusion (Siebesma and Teixeria 2000)

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial z}(-\overline{wc}) = -\frac{\partial}{\partial z}[-k_c \frac{\partial \overline{c}}{\partial z} + M(c_u - \overline{c})]$$

small eddies   strong updrafts

iv) TKE (Turbulent Kinetic Energy) diffusion (Mellor and Yamada 1982)

TKE equation :
$$\frac{\partial \overline{u_i u_j}}{\partial t} + u_j \frac{\partial \overline{u_i u_j}}{\partial x_j} = -\frac{\partial}{\partial x_k}[\overline{u_i u_j u_k} + \frac{1}{\rho} \cdots]$$

$$\overline{u_i u_j} ==> k_z = \text{ fn (TKE)}$$

3.4 Local versus nonlocal
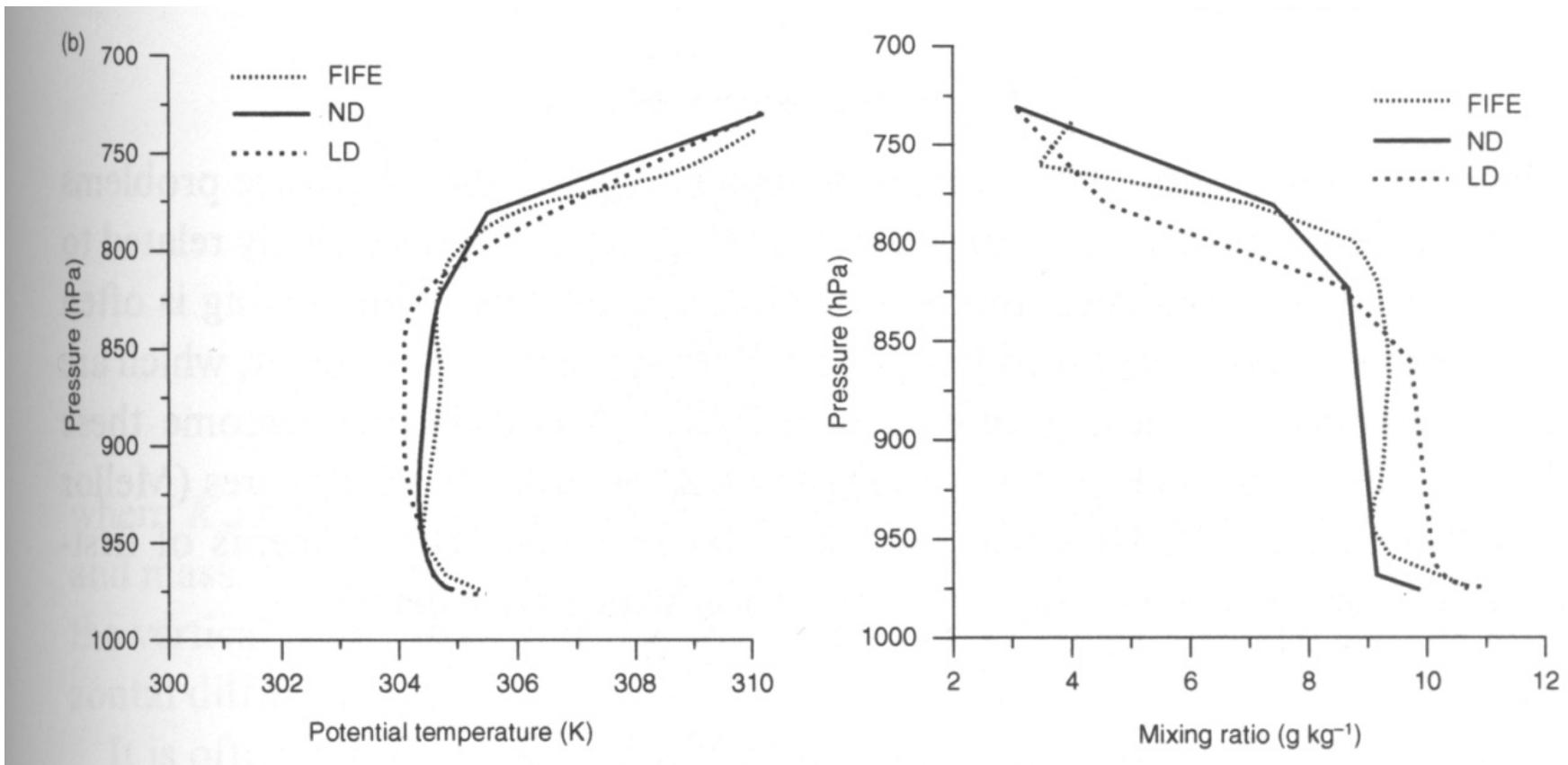
Local scheme (LD) typically produces unstable mixed layer in order to transport heat upward. But, observation (FIFE) shows near neutral or slightly stable BL in the upper part of BL

Hong and Pan (1996)

4. Gravity Wave Drag

- GWDO : GWD induced by sub-grid scale orography

- GWDC : GWD induced by precipitating deep convection

4.1 Concept

This scheme (GWDO) includes the effect of mountain induced gravity wave drag from sub-grid scale orography including convective breaking, shear breaking and the presence of critical levels. Effects are strong in the presence of strong vertical wind shear and thermally stable layer.

Vertically propagating wave

Breaking wave region
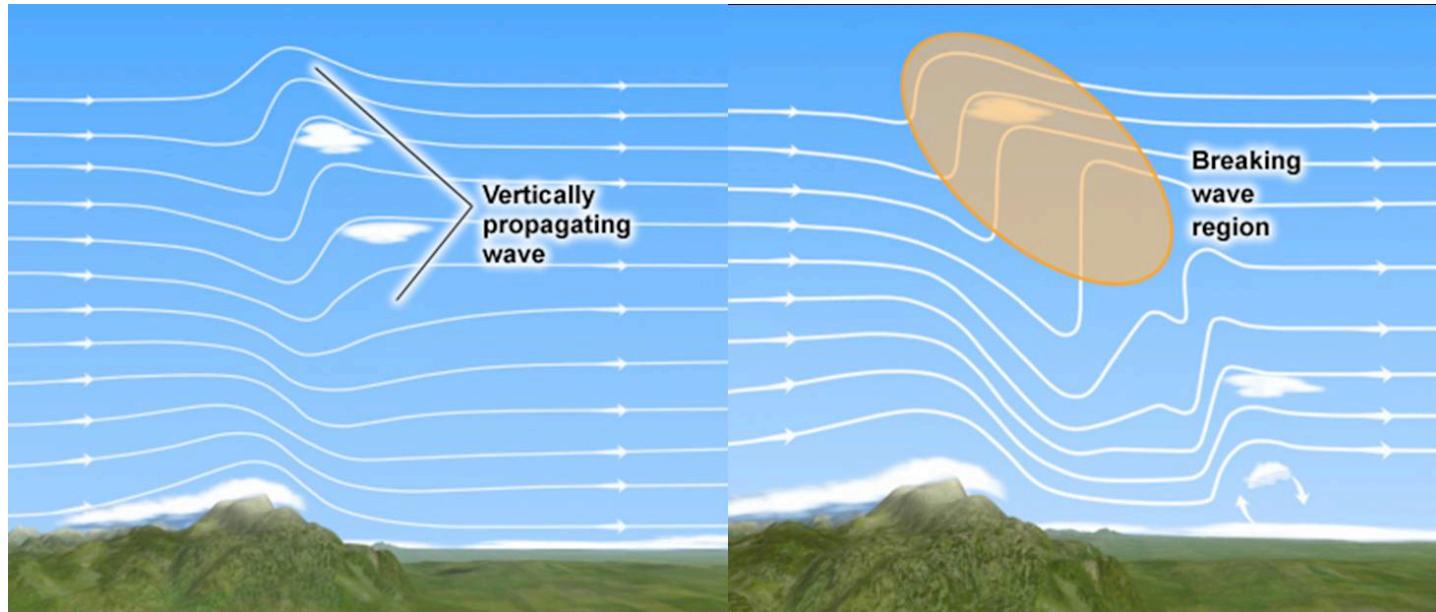
* In smoothed model orography, momentum stress near mountain cannot be generated

4.2 Enhanced lower tropospheric gravity wave drag (Kim and Arakawa 1995)

$$\frac{\partial u}{\partial t} < 0$$

$$\frac{\partial u}{\partial t} = 0 \qquad \frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial \tau_x}{\partial z}$$

$$\frac{\partial u}{\partial t} < 0 \qquad \frac{\partial v}{\partial t} = -\frac{1}{\rho}\frac{\partial \tau_y}{\partial z}$$

Stress at reference level :

$$\tau_0 = -E\frac{1}{\Delta x}\frac{\rho_0 U_0^3}{N_0}\frac{Fr^2}{Fr^2 + 0.5/OC}, \quad U_0 = \frac{1}{h}\int_{k=1}^{k=kpbl} U dz$$
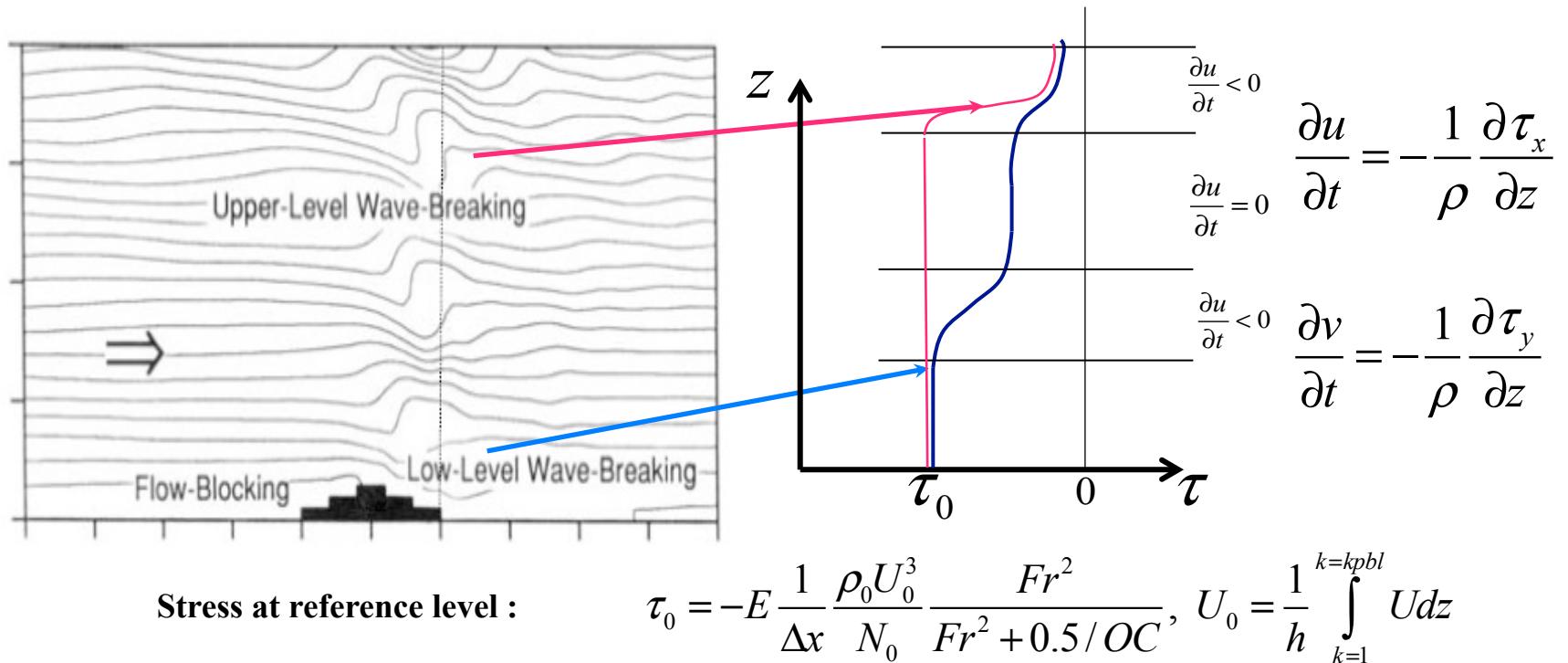
Reference level (KA95) : Max (2, KPBL)

Conventional : the conventional Ri number-based wave- breaking mechanism
   using the saturation hypothesis, which works mainly in the upper atmosphere

Advanced: the higher-moment orographic statistics-based wave- breaking mechanism using half-theory
   (Scorer parameter ~ BVF**2 / U**2) and half-empiricism obtained from mesoscale mountain wave
   simulations, which breaks in the lower atmosphere as well as upper layer, together with flow blocking

27

4.3 Impact of GWDO

Zonal-averaged zonal wind (96/97 DJF)

NOGWDO

> **Contour : Zonal averaged zonal wind**
> **Shaded: Deviations from the RA2**
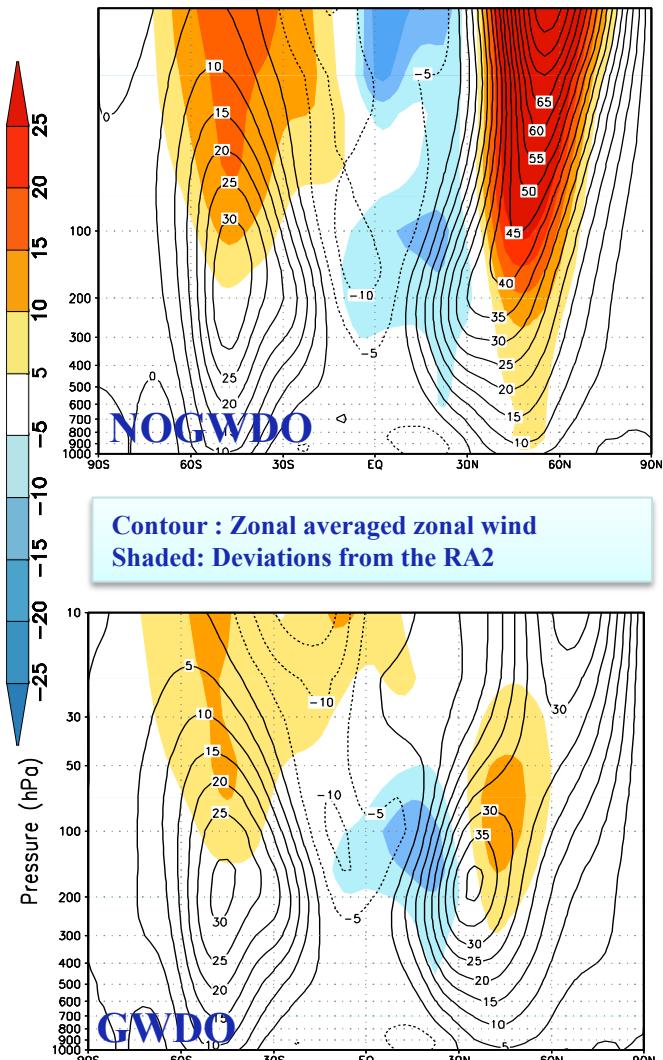
GWDO

➜ Improves the upper level jets
(Kim and Hong, 2009)

Wind speed (3-5 Jan. 2010)

CTL

Shading: Bias
Contour: RMSE

SOP
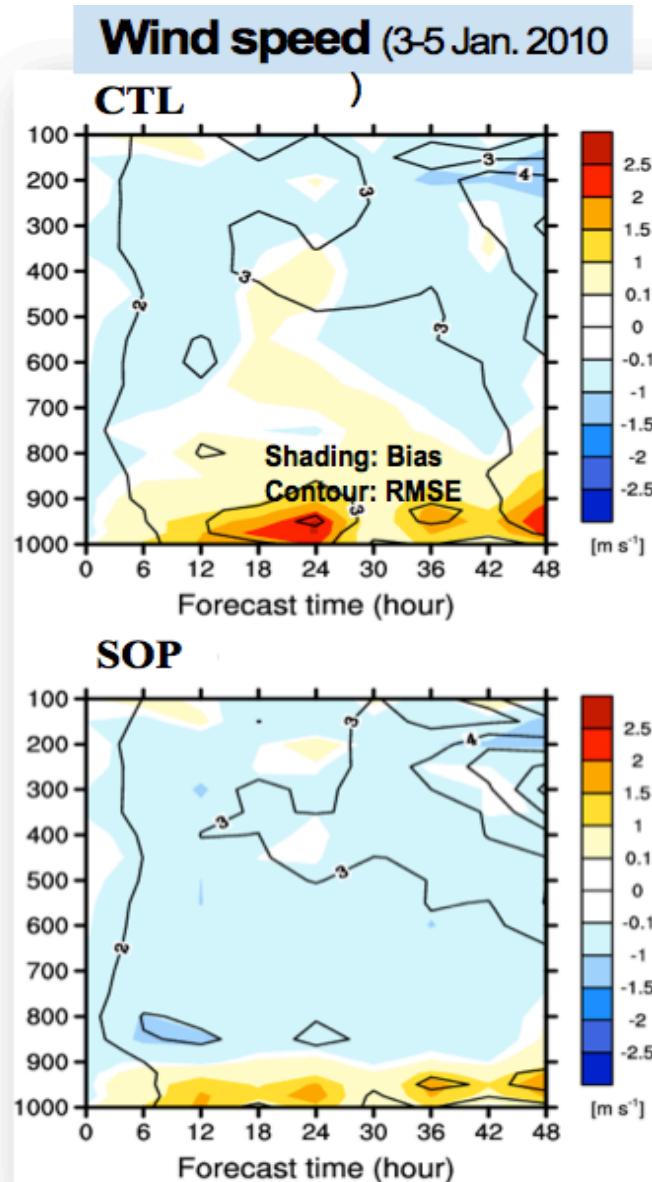
Flow blocking ➜ Improves the low-level
winds (Choi and Hong, 2015)

4.4 Convective GWD (CGWD) or non-orographic GWD

CGWD parameterizations
- Chun and Baik (1998, 2002): The momentum flux spectrum for the CGWD parameterization was **first analytically formulated**
- Song and Chun (2005): **Nonstationary parts** of convective GWs were included in the parameterization
- Song and Chun (2008): **Ray-based parameterization** that can represent a three-dimensional propagation of GWs was developed
- Choi and Chun (2011): Two free parameters, the **moving speed of the convective source** and **wave-propagation direction**, were determined
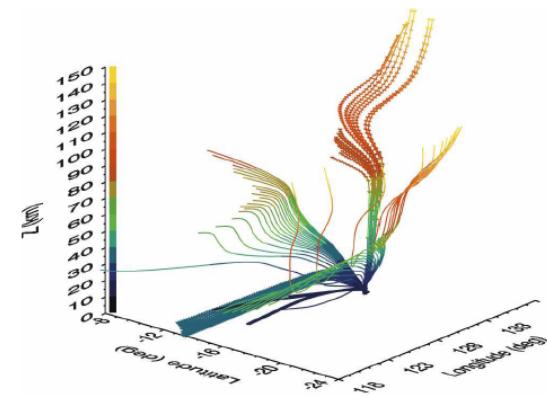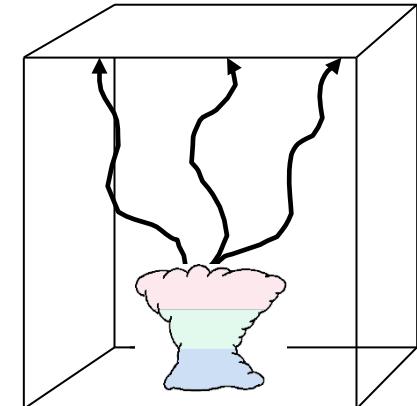
Jet/Front GWD parameterizations
- At this moment, there is **no source-level momentum flux formulation** of jet/front GWs, due primarily to the lack of complete understanding of generation mechanisms
- Charron and Manzini (2002), Richter et al. (2010): **Frontogenesis function** was adopted to diagnose the generation of frontal GWs

* It is very rare to have this CGWD or no_mtn_GWD

Frontogenesis function at 600 hPa (20000721 12UTC)

frontgf [K^2(100km)$^{-2}$h^{-1}]
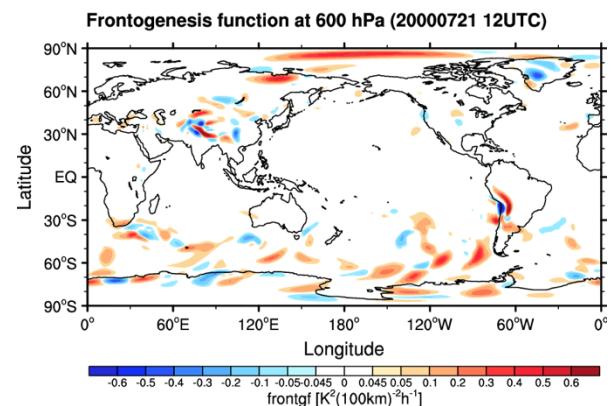
4.5 Improvement by GWDC (Chun and Baik 1998, Jeon et al. 2010)

a) SAS_CB98 Zonal wind difference

c)

Contour : Zonal averaged
Shaded: Deviations from the RA2
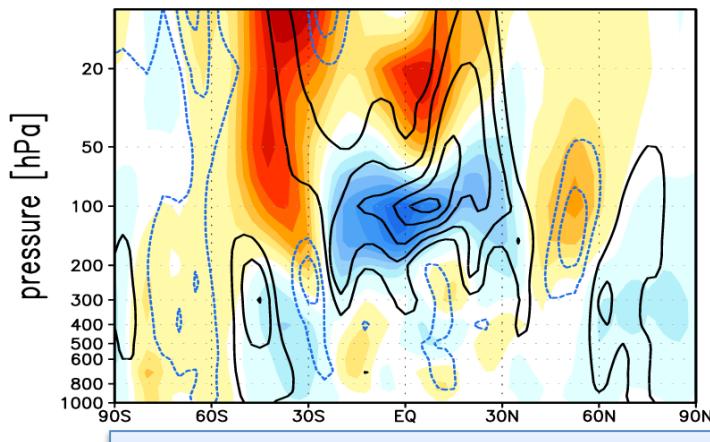
a) SAS_CB98 Temperature difference
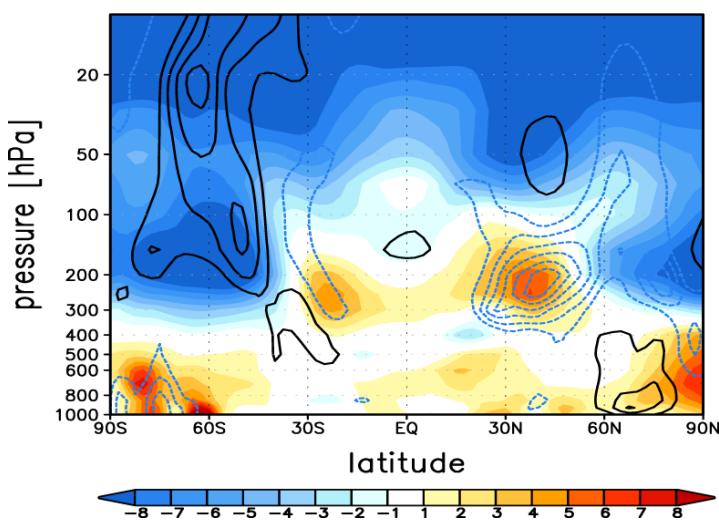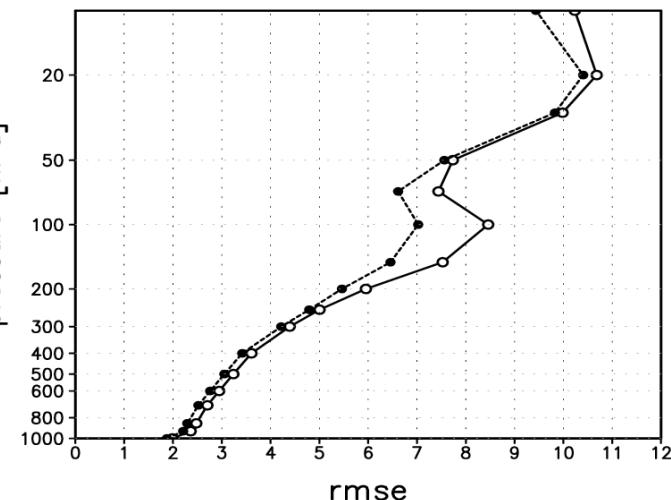
b)
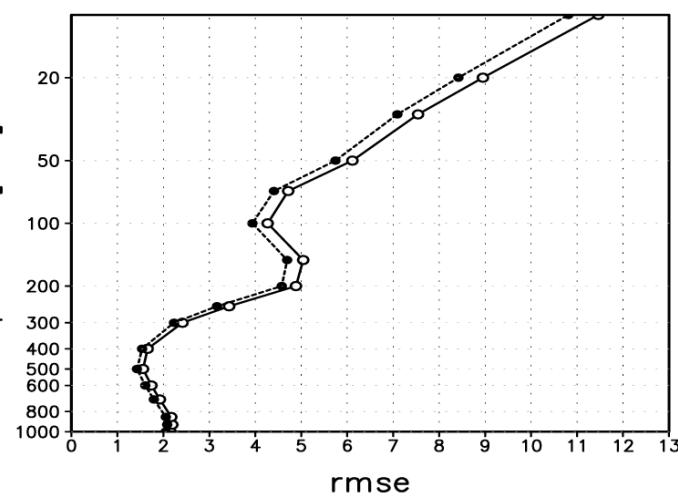
Wind and temperature RMSE are reduced in upper atmosphere

Precipitation Processes

Concept : precipitation algorithms (CPS and MPS)

- In real atmosphere, dynamical motion -> RH > 1 => clouds form -> produces rain

- In modeled atmosphere, RH < 1

  But generate clouds by sub-grid scale motion → requires parameterized process
  (it is often related to the deep convection processes)
  Deep convection : 2~10 km

$\overline{RH} < 1$ $RH = 1$
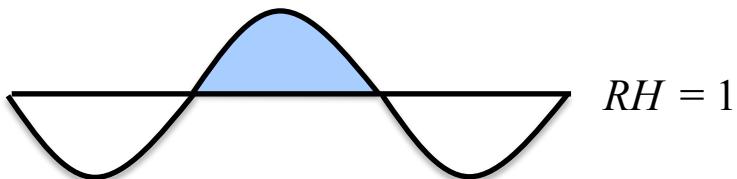
$\Delta x ==> 0$, more grid-resolvable precipitation
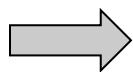
Thus, we need the cumulus parameterization scheme to account for releasing conditional instability due to subgrid scale motion

- Grid-resolvable (Microphysics scheme : MPS)   : Supersaturation → clouds
- Subgrid scale (Cumulus parameterization scheme : CPS) : CAPE removal → clouds

5. Cumulus parameterization scheme

5.1 Concept

Parameterized convection
Deep convection
Subgridscale precipitation
Implicit precipitation

- represents deep precipitating convection and feedback to large-scale
- must formulate the collective effects of subgridscale clouds
  in terms of the prognostic variable in grid scale

Jul 25, 2010, Seoul
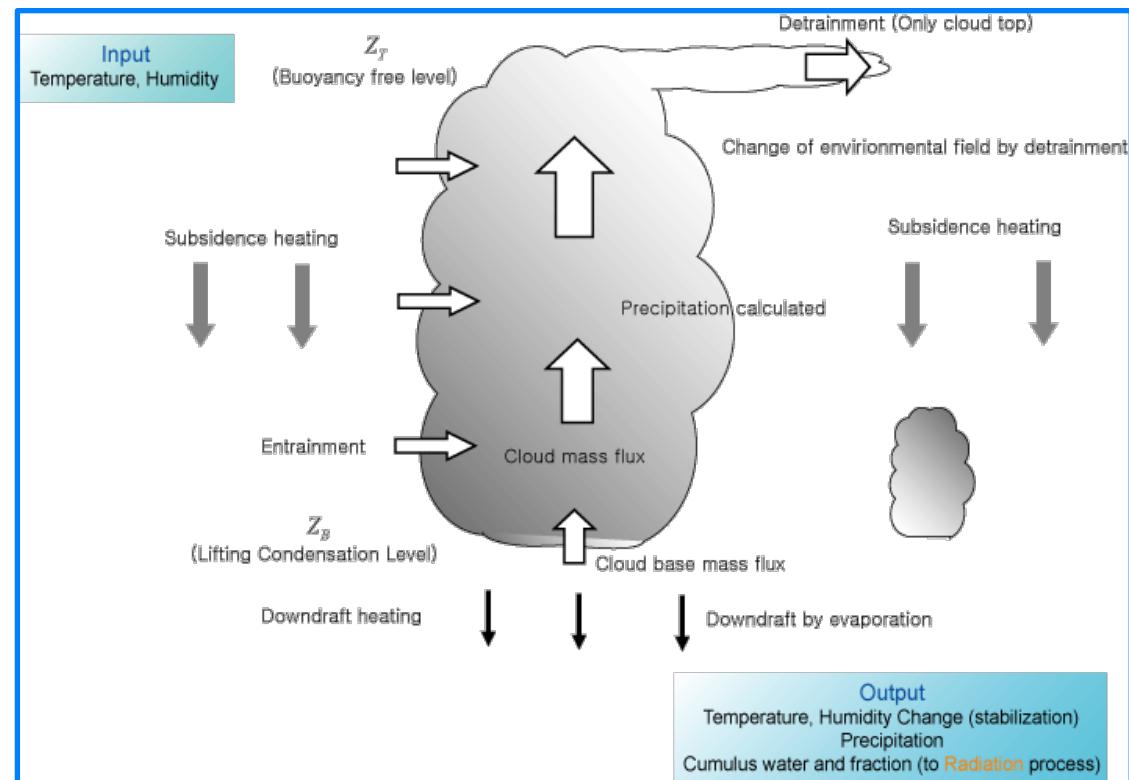
Processes CP Schemes Need to Account For

b

Convective Initiation

Deep Convection

Shallow Convection at Top of Mixed Layer

Mixed Layer
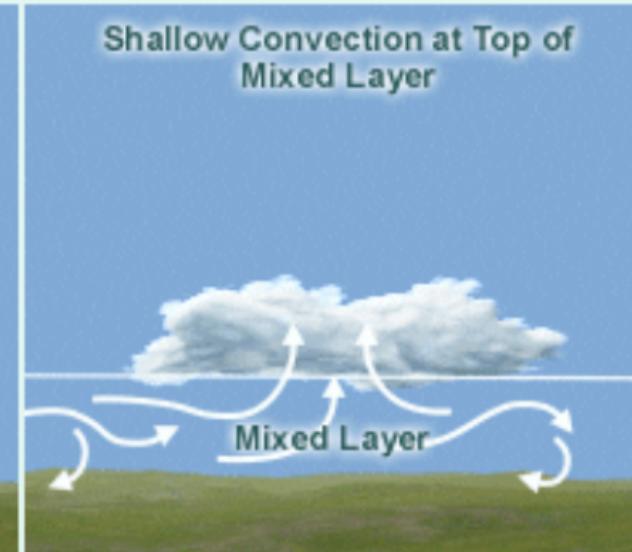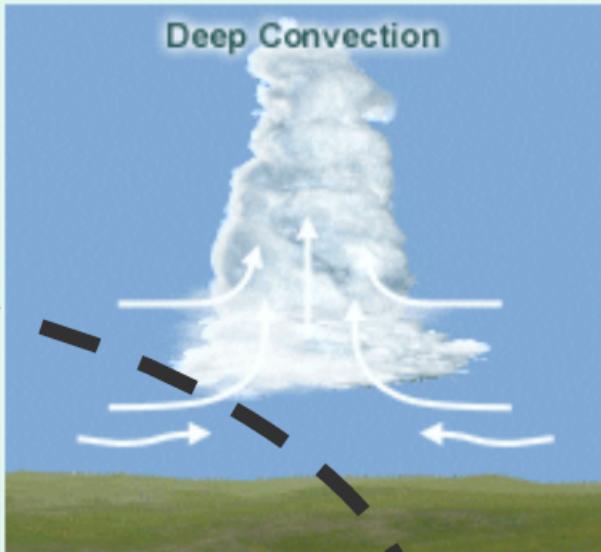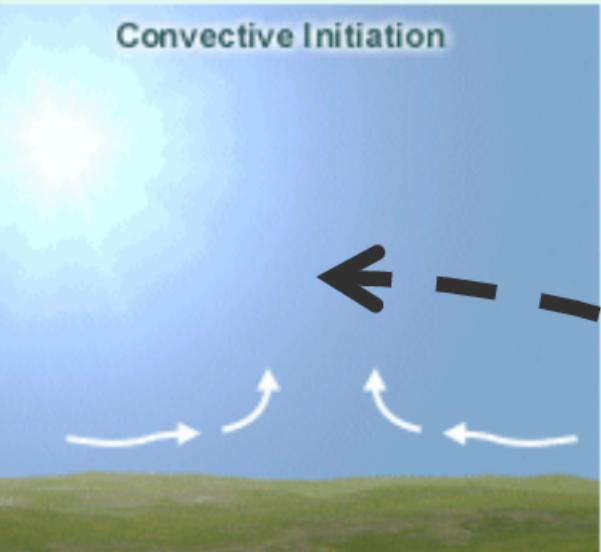
Vertical Heating / Cooling

Net Max Heating

Evaporation & Cooling Transported Downward

Heat Transported Upward

Max Condensation

Vertical Drying / Moistening

Detrainment

Compensating Subsidence

Drying Transported Downward

Moisture Transported Upward

Precipitation

(By-product)
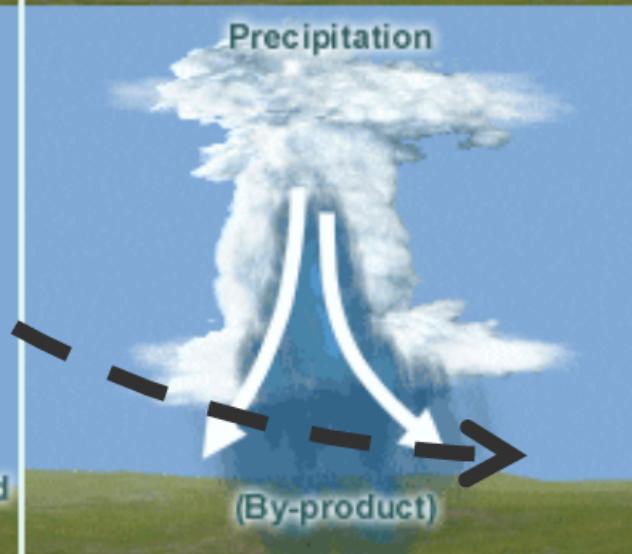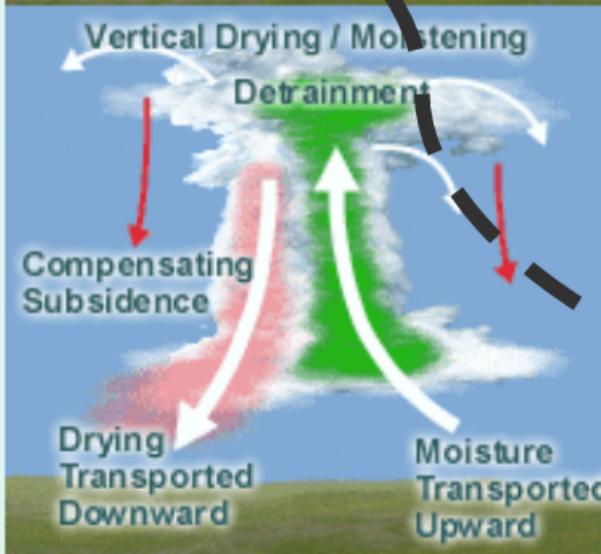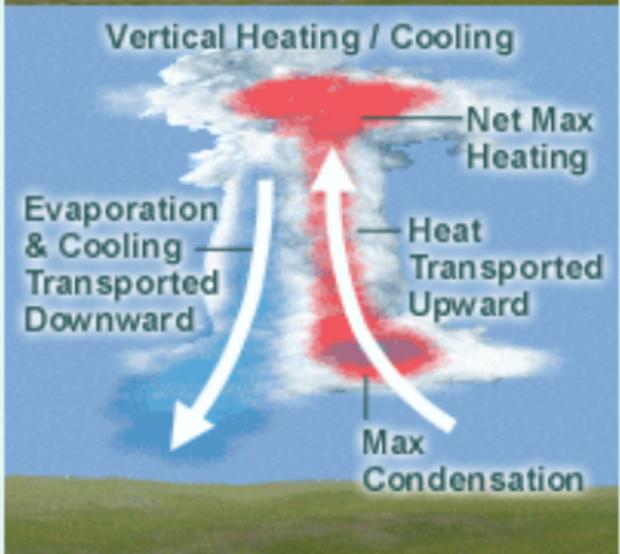
The COMET Program

CPS does not consider the detailed evolution of convection !

precip is found by adding up latent heat (blue <0, purple>0)

enthalpy adjustment shifts reference profile to the left

precip also equals the amount of moisture removed (green>0, orange<0)
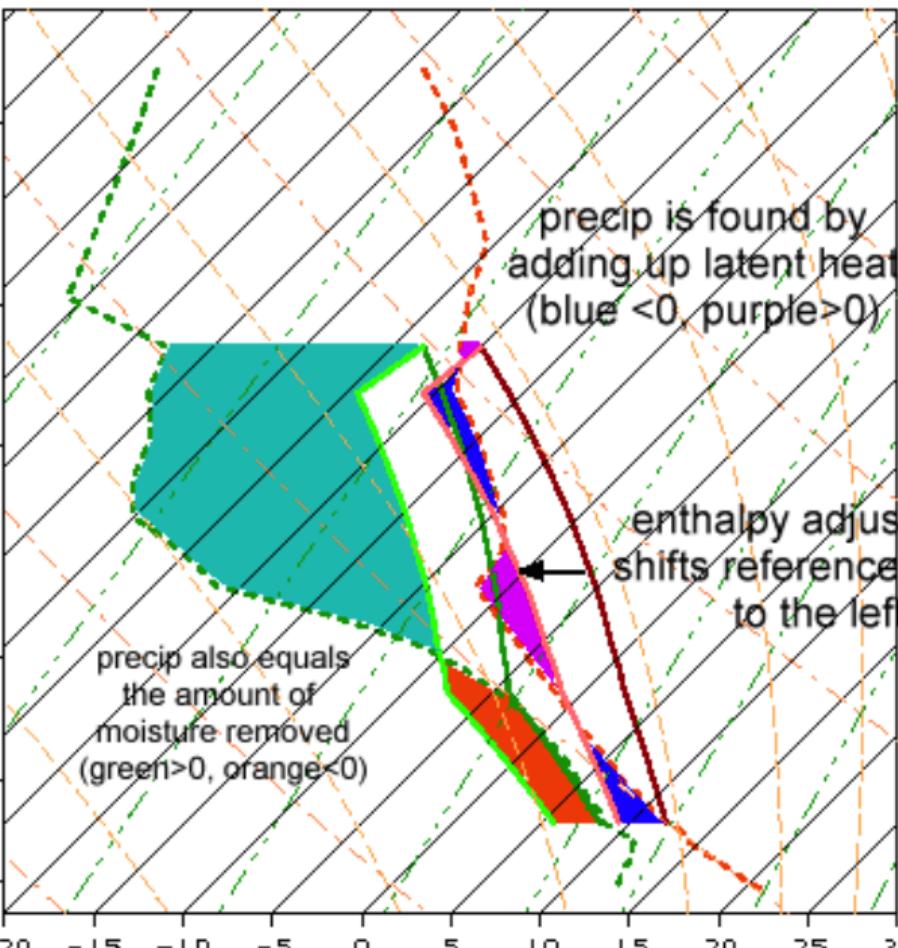
Charleston SC 22 Apr 1998 2200 UTC
(dashed=model, darker red/green=1st guess BMJ,
lighter red/green=enthalpy adjusted BMJ profiles)

post-convective adjustment, 1h later
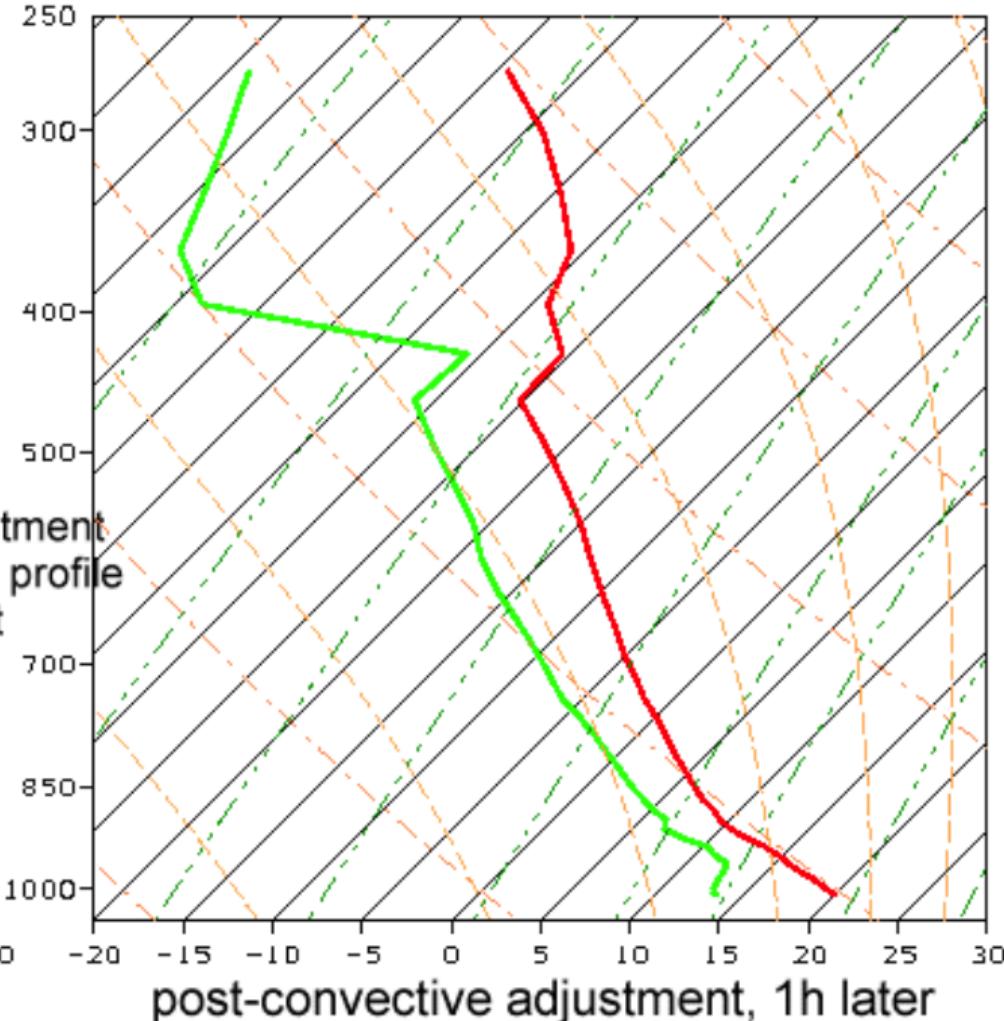
Michael Baldwin

CPS consider changes in profile before and after convection

5.2 Kuo scheme (1965)

: Cloud is formed in proportional to column-integrated moisture convergence

$$M_t = -\frac{1}{g} \int_0^{P_s} \nabla \cdot (vq) dp + F_{g_s}$$

$$\int_0^{P_s} \frac{\partial q}{\partial t} dp = gbM_t, \quad b : \text{moistening factor}$$

$$\int_0^{P_s} \theta_c dp = gL(1-b)M_t \quad \frac{\theta_c}{\pi} = \frac{\theta_a - \theta}{\tau}$$

- Modified Kuo scheme

Krishnamurti el al. (1980, 1983) : proportional to

vertical advection of moisture

$$M_t = -\frac{1}{g} \left\{ \int_0^{P_s} \omega \frac{\partial q}{\partial p} dp + F_{q_s} \right\}$$

Anthes (AK : 1977) : a revised moistening factor and parcel buoyancy

$$b = \left(\frac{1 - RH}{1 - RH_c} \right)^n$$

- Heating and moistening profiles (prescribed)

$$\frac{d\theta}{dt} = \frac{1}{\pi}\left[gL(1-b)M_tQ_1 + Q_r\right]$$

$$\frac{dq}{dt} = -g(1-b)M_tQ_2 \qquad \int_0^{P_s} Q_1 dp = \int_0^{P_s} Q_2 dp = 1$$
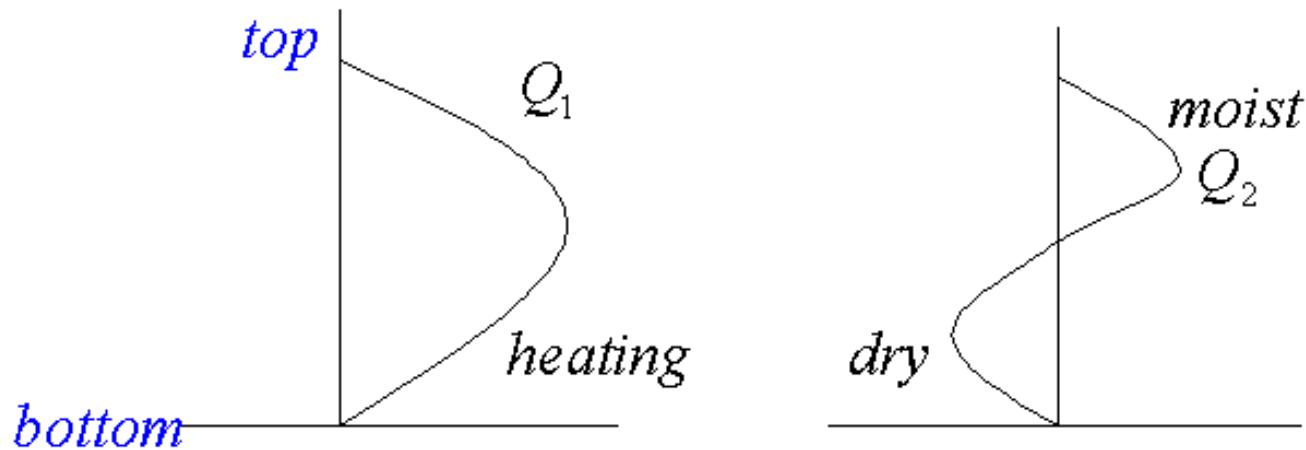
- Kuo type scheme has been widely used before 1990

5.3 Betts-Miller scheme (1986)

: adjust toward reference profiles that are based on observational evidence of convective equilibrium
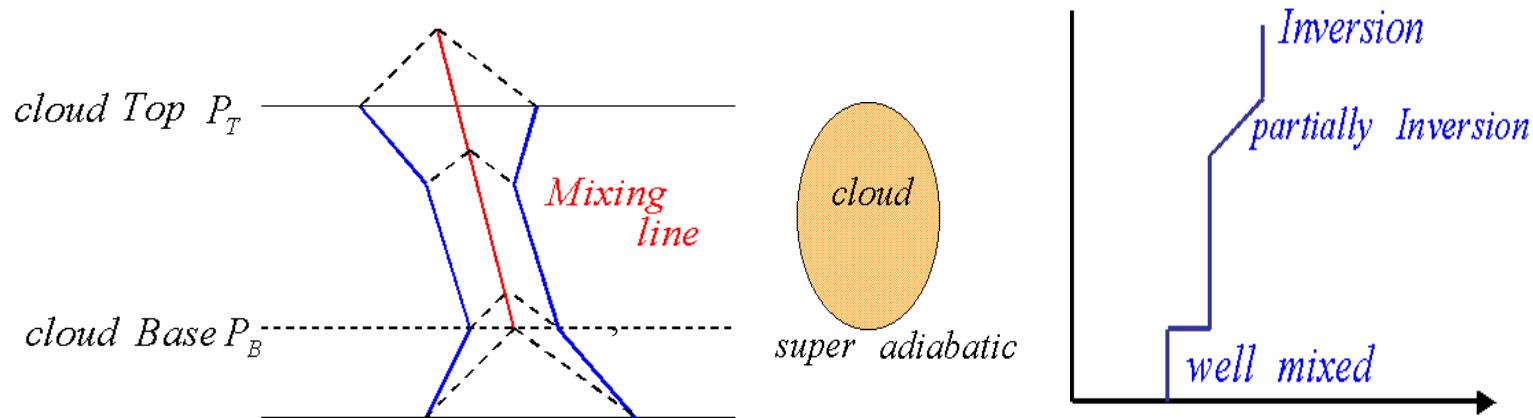
Reference profile to be adjusted : originally based on tropical cyclones

$$\theta'_R(P) = \bar{\theta}(P_B) + \beta\, M_\theta (P - P_B)$$

$$\frac{\partial q}{\partial p} = \beta \left(\frac{\partial q}{\partial p_*} \right)_M \qquad \beta = \frac{\partial p^*}{\partial p} \qquad\qquad p^* : \text{saturation pressure (= 1.2 for example)}$$

$$M_\theta = 0.85 \left(\frac{\partial \theta^*}{\partial P^*} \right)_M \qquad\qquad \text{M : Mixing line}$$

Energy Constraints : $\displaystyle \int_{P_B}^{P_{T+1}} C_P \left(T_R - \bar{T} \right) dp = \int_{P_B}^{P_{T+1}} \left(q_R - \bar{q} \right) dp = 0$

- Convective tendencies & Precipitation

$$\left(\frac{\partial \overline{T}}{\partial t}\right)_{Cu} = \frac{T_R - \overline{T}}{\tau}$$

$$\left(\frac{\partial \overline{q}}{\partial t}\right)_{Cu} = \frac{q_R - \overline{q}}{\tau}$$

$$\Pr ecip = \int_{P_0}^{P_T}\left(\frac{q_R - \overline{q}}{\tau}\right)\frac{dP}{g} = -\frac{C_P}{L}\int_{P_0}^{P_T}\left(\frac{T_R - \overline{T}}{\tau}\right)\frac{dp}{g}$$

cloud top

REFERENCE TEMPERATURE

moist adiabat $\left(\frac{d\theta}{dp}\right)_{mad}$

ambient freezing level

$0.9 * \left(\frac{d\theta}{dp}\right)_{mad}$

Betts (1986)   cloud base
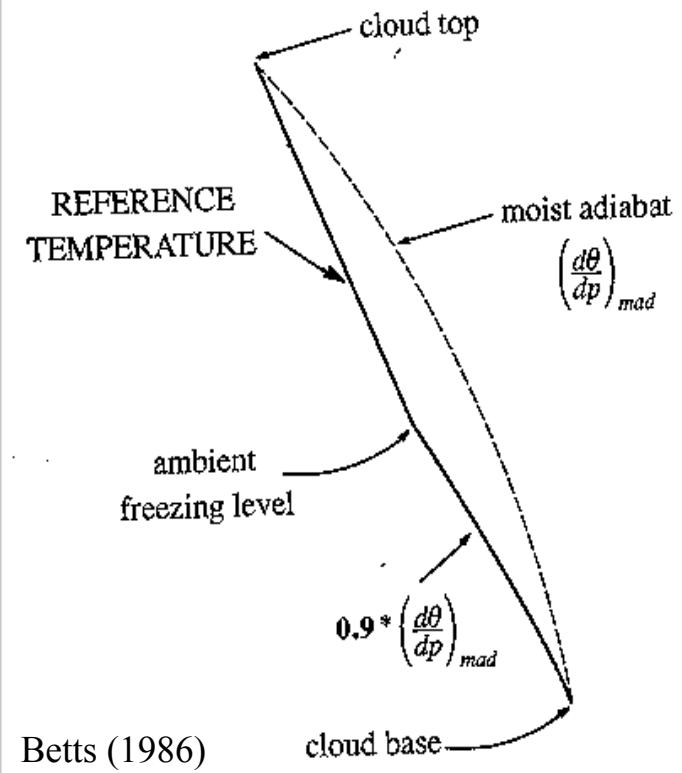
- Remarks : -Manabe   (hard adjustment : toward a moist adiabat)
-Kuo, BM (soft adjustment : toward reference profiles

5.4 Mass-flux schemes : Arakawa-Schubert (1974)

i) Concept

-- Mass flux approach, cloud ensemble, quasi-equilibrium
-- Theoretical frame work for CPS

- Area is large enough so that cloud ensemble can be a statistical entity
- Area is small enough so that cloud environment is approximately uniform horizontally
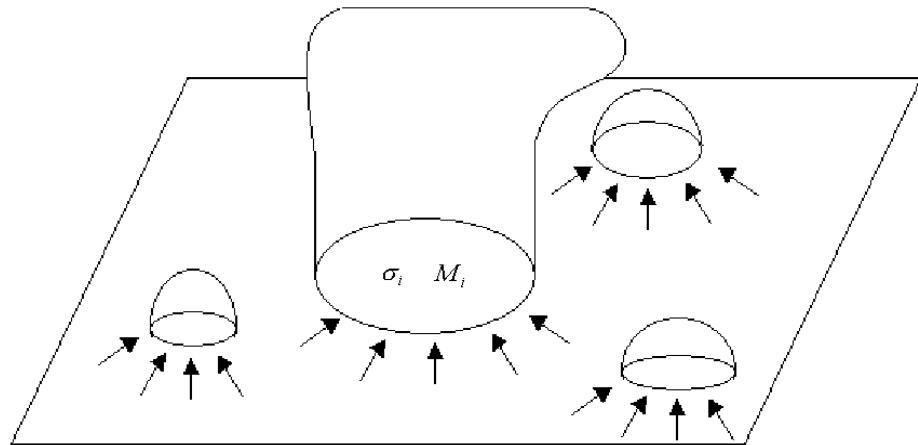
M_i : vertical mass flux through ith cloud

σ_i : fractional area covered by ith cloud

$M_c \equiv \sum_i M_i$: total vertical mass flux

environment

$$\rho M = M_c + \tilde{M}$$

: net mass flux/unit large-scale horizontal area

ii) Quasi-equilibrium : cloud forcing ~ large-scale adjustment

: CPS computes the warming (cooling) in the grid box due to adiabatic descent (ascent),
rather than computing latent heat release in cloud models
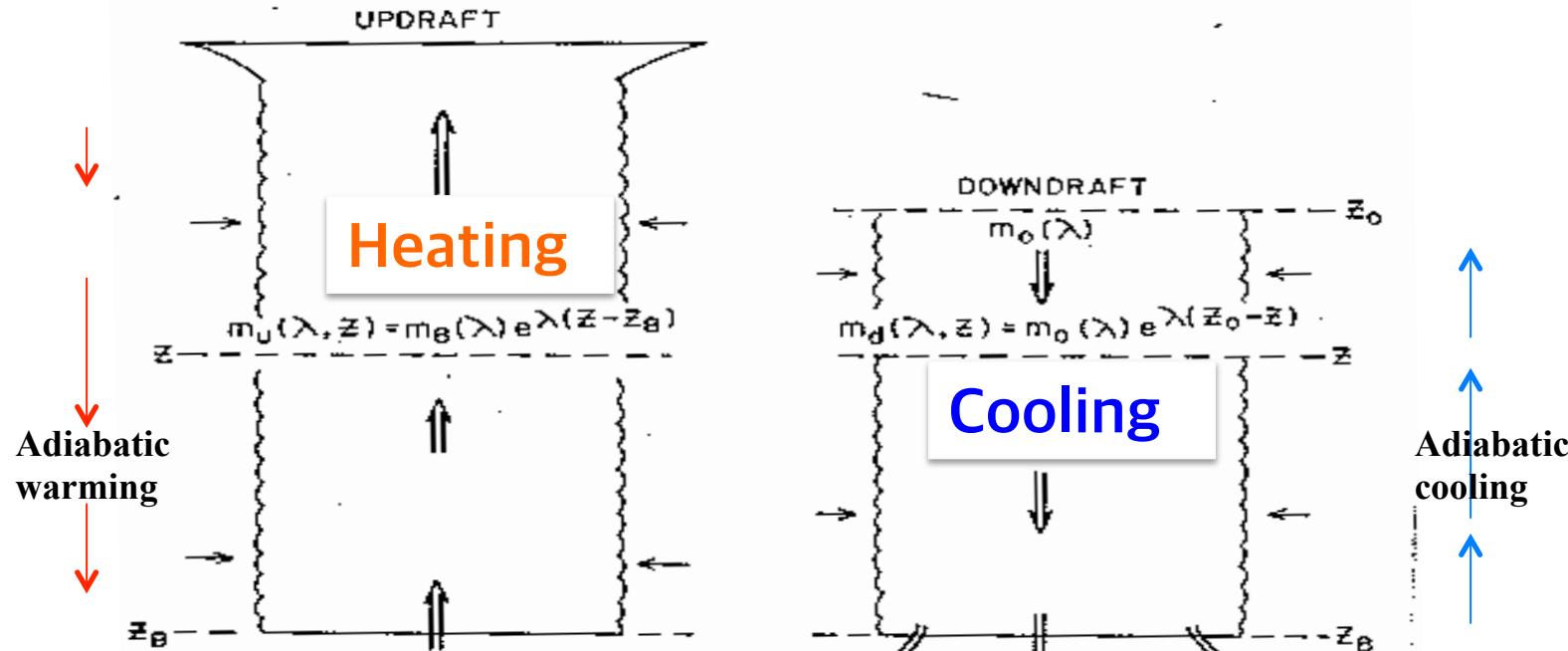
FIG. 4.10. Model for updraft and downdraft of cloud type λ (from Johnson 1976).

iii) Energy budget equations

Large-scale flux across grid box   Exchange of S between environment and clouds

$$\frac{\partial}{\partial t}\rho(1-\sigma_c)\tilde{s} = -\vec{\nabla}\cdot\overline{(\rho\tilde{V}S)} - \frac{\partial}{\partial Z}(\tilde{M}\tilde{S}) - \sum_i\left(\frac{\partial M_i}{\partial Z} + \rho\frac{\partial \sigma_i}{\partial t}\right)S_{i_b} - LE + \tilde{Q}_R \quad \text{: Environment MSE}$$

$$\frac{\partial}{\partial t}\rho\sum\sigma_i s_i = -\frac{\partial}{\partial z}\left(\sum_i M_i s_i\right) + \sum_i\left(\frac{\partial M_i}{\partial z} + \rho\frac{\partial \sigma_i}{\partial t}\right)S_{ib} + \sum_x\left(LC_i + Q_{Ri}\right) \quad \text{: in-cloud MSE}$$

$S_i : C_pT + gz$ (dry static energy) of i$^{\text{th}}$ cloud

$S_{ib} : C_PT + gz$ of the air entraining into or detraining from the i$^{\text{th}}$ cloud

C_i : condensation in the i$^{\text{th}}$ cloud

E : evaporation of liquid water in the environment

Q_r : Radiative heating

- Entrainment : $\quad \dfrac{\partial M_i}{\partial z} + \rho\dfrac{\partial \sigma_i}{\partial t} > 0, \quad S_{ib} = \tilde{S}$

- Detrainment : $\quad \dfrac{\partial M_i}{\partial z} + \rho\dfrac{\partial \sigma_i}{\partial t} < 0, \quad S_{ib} = S_i$

41

iv) Approximation

- Assume $\quad \sigma_c \ll 1 \;, \quad \bar{s} \simeq \tilde{s}$

$$\frac{\partial}{\partial t}\rho\bar{s} = -\nabla\cdot(\rho\overline{\vec{v}\,s}) - \frac{\partial}{\partial z}(\rho\overline{ws}) - \overline{\nabla\cdot(\rho\vec{v}s - \rho\overline{\vec{v}}\,\bar{s})}$$

$$+ M_c\frac{\partial\bar{s}}{\partial z} - \sum_{dc}(\frac{\partial M_i}{\partial z} + \rho\frac{\partial\sigma_i}{\partial t})(\delta_i - \bar{s}) - LE + \dot{\theta}_R$$

Adiabatic warming due to hypothetical
subsidence between the clouds

Detraining clouds

detrainiment, entrainment

$$\frac{\partial}{\partial t}\rho\bar{q} = -\nabla\cdot(\rho\overline{\vec{v}\,q}) - \frac{\partial}{\partial z}(\rho\overline{wq}) - \overline{\nabla\cdot(\rho\vec{v}q - \rho\overline{\vec{v}}\,\bar{q})}$$

$$+ M_c\frac{\partial\bar{q}}{\partial z} - \sum_{dc}(\frac{\partial M_i}{\partial z} + \rho\frac{\partial\sigma_i}{\partial t})(q_i - \bar{q}) - E$$

- Spectral cloud ensemble :

$$M_c(z) = \int_0^{\lambda_{max}} m(z,\lambda)d\lambda$$

Sub-ensemble

mass flux of between λ and $d\lambda + \lambda$

$$= \int_0^{\lambda_{max}} m_B(\lambda)\eta(z,\lambda)d\lambda$$

Mass flux at cloud base

$$\eta(z,\lambda) \equiv \frac{m(z,\lambda)}{m_B(\lambda)} \quad ; \quad \text{normalized subensemble mass flux}$$

42

v) Closure

$$\frac{\partial m(z,\lambda)}{\partial z} = \mu(z,\lambda)\eta(z,\lambda)$$

$$\eta(z,\lambda) = e^{\lambda(z-zB)} \quad ; \text{ mass flux profile}$$

- Cloud work function : measure of buoyancy

$$A(\lambda) = \int_{z_B}^{z_D(\lambda)} \eta(z,\lambda) g \frac{T_c(z,\lambda) - \overline{T}(z)}{\overline{T}} dz$$

- Q-G equilibrium

$$\frac{dA(\lambda)}{dt} = \left.\frac{dA(\lambda)}{dt}\right|_{LS} + \left.\frac{dA(\lambda)}{dt}\right|_{C} \simeq 0$$

Large-scale forcing   Adjustment
>0 : destabilized   <0 : stabilization

Kernel : Cloud scheme kinetic energy

$$K_{ij} = \frac{A_i' - A_i}{(m_B \Delta t)} \qquad \sum_{j}^{i_{max}} K_{ij}(m_B \Delta t)_j + F_i = 0 \quad => m_B$$

$$\longrightarrow \text{ compute } \frac{\partial \overline{s}}{\partial t}, \frac{\partial \overline{q}}{\partial t} \text{ with } \eta, m_B$$

43
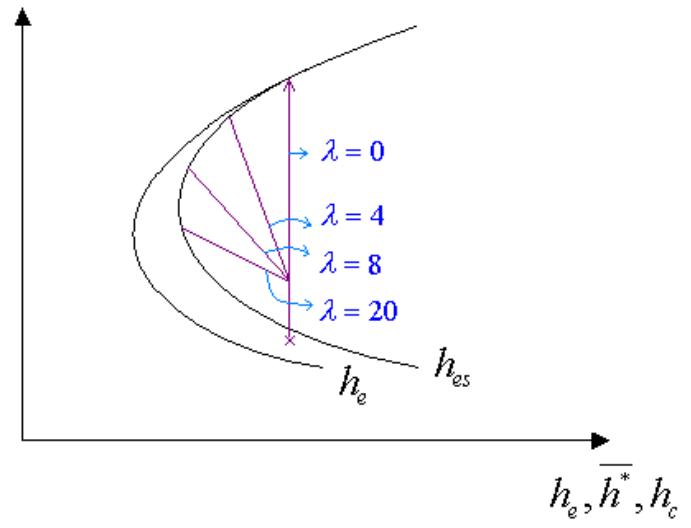
5.5 Other schemes

* Arakawa-Schubert type mass flux schemes

Grell scheme (1993) : Updraft/downdraft couplet without lateral mixing to find the deepest cloud

Simplified AS (SAS, Han and Pan 2011): revised cloud physics from the Grell

Relaxed AS (RAS, Moorthi and Suarez 1992): linearized profile function

* Other mass flux schemes : Low-level control convective schemes (Stensrud 2007)

Kain and Fritsch (2004) : CAPE based sophisticated convective plume model

Emanuel (1991) : Stochastic mixing cloud model

Tiedtke (1989) : Large-scale moisture convergence (KUO) based mass flux (ECMWF IFS model)

Gregory-Rowntree (1990): Parcel buoyancy based turbulence in cloud model (UK model)

6. Shallow Convection

6.1 Concept

more vigorous vertical mixing of q and T above the mixed layer top. With the enhanced vertical eddy transport between LCL and inversion level, this process does not allow the excess moisture trapped near the surface in synoptically inactive regions (non-precipitating convection).

➔ Cooling and moistening above LCL and heating and warming below.

6.2 Classification

- Moist adjustment type : Betts and Miller (1993), Lock et al. (2000), Tiedtke (1983)
- Mass flux type : Kain (2004), Park and Bretherton (2009), Han and Pan (2011)

Tiedtke (1983)

$$\frac{\partial T}{\partial t} = \frac{1}{\rho} \frac{\partial}{\partial z} \left(\rho K \left[\frac{\partial T}{\partial z} + \Gamma \right] \right)$$

$$\frac{\partial q}{\partial t} = \frac{1}{\rho} \frac{\partial}{\partial z} \left(\rho K \frac{\partial q}{\partial z} \right)$$

Han and Pan (2011)

$$\frac{1}{\eta} \frac{\partial \eta}{\partial z} = \varepsilon - \delta$$

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

$$\frac{\partial [\eta (q_v + q_l)]}{\partial z} = \eta [\varepsilon \bar{q}_v - \delta (q_v + q_l) - r]$$

45

6.3 Impact of the shallow convection scheme (SCV)

: JJA 1996 simulation in a GCM

Temperature

RH

NO SCV – RA2

SCV – NO

dry

moist

mixing
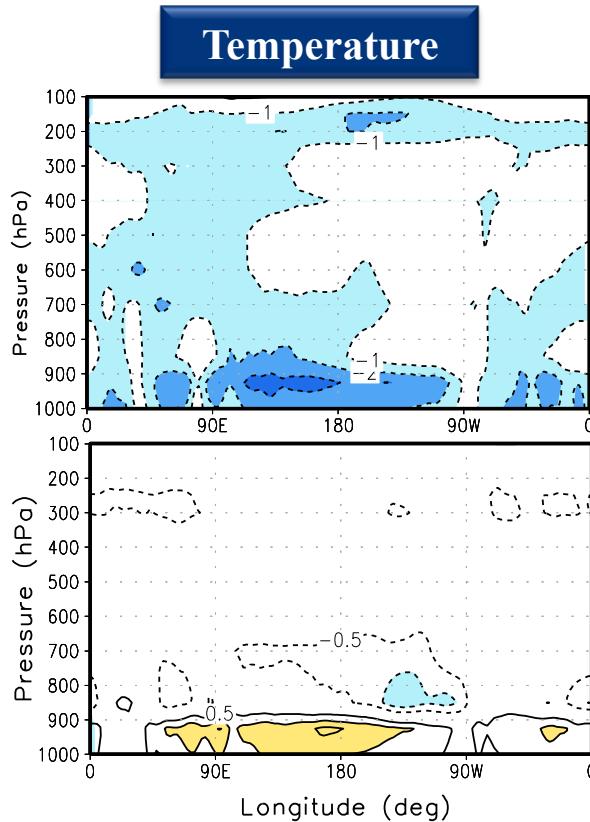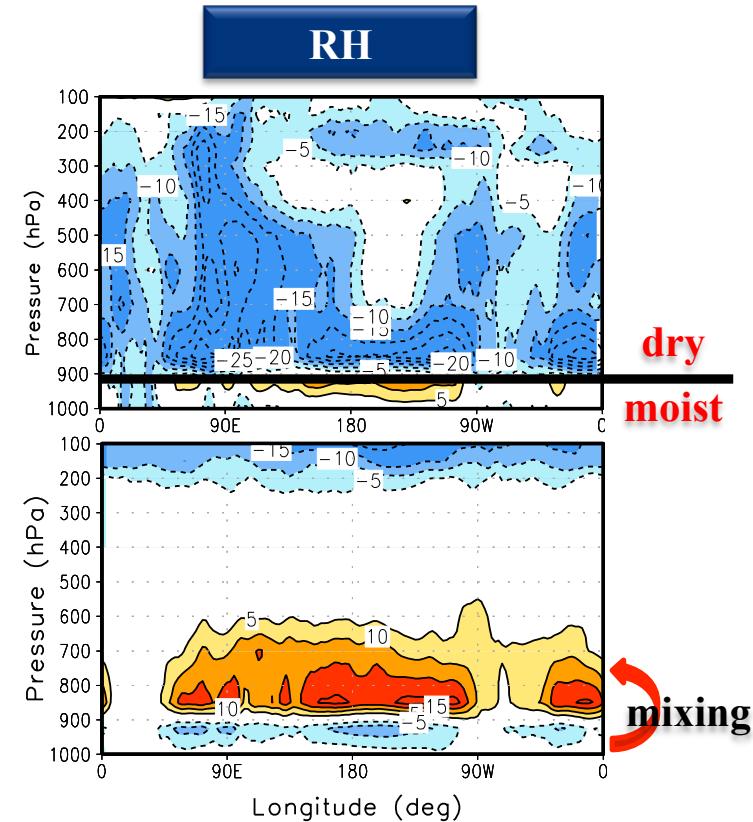
* SCV plays crucial role over the oceans.

7. Microphysics scheme

large-scale precipitation
grid-resolvable scale precipitation
explicit moisture scheme
cloud scheme
non-convective precipitation scheme

7.1 Concept

- Remove supersaturation after deep and shallow convection, and feedback to large-scale

7.2 Classification : according to the complexity in microphysics

i) Diagnostic : condensation, evaporation of falling precipitation

ii) Bulk microphysics : hydrometeors with size distribution in inverse-exponential function
- Single moment : predict mixing ratios of hydrometeors
- Double moment :   + number concentrations
- Triple moment :   + reflectivity

iii) Bin microphysics : divides the particle distribution into a number of finite size or mass categories.

7.3 Precipitate size distributions

Marshall and Palmer(1948) : exponential law
Heymsfield and Platt (1984) : Power law

$$N_R(D_R) = aD_R{}^b$$

The rain and snow particles are assumed to follow the size distribution derived by Marshall and Palmer(1948), and Gunn and Marshall(1958), respectively. The size distributions for both rain and snow are formulated according to an inverse-exponential distribution and its formula for rain can be expressed by

$$N_R(D_R) = N_{0R} \exp(-\lambda_R D_R)$$

for rain, where N_{0R} is the intercept parameter of the rain distributions. Slope parameter is

$$\lambda_R = \left(\frac{\pi \rho_w N_{0R}}{\rho q_R} \right)^{1/4}$$

$\log_{10}(N(D))$

$\leftarrow \log_{10}(N_{0R})$

Fig. 9.21. Evolution of a drop spectrum in a subsaturated rainshaft including the effects of coalescence and breakup. The spectrum at the top of the rainshaft is Marshall–Palmer with a rainfall rate of 110 mm h^{-1}. (······), 0 km; (---), 1 km; (−), 2 km; R = 110 mm h^{-1}; t = 24 min. From Tzivion et al. (1989). *Journal of Atmospheric Sciences*, **46**, 21. American Meteorological Society. Reproduced with permission

$$\Gamma(x) = \int_0^\infty t^{x-1} \exp(-t)dt$$

$$\int_0^\infty D_R{}^{4-1} \exp(-\lambda_R D_R)dD_R$$

$$= \Gamma(4)/\lambda_R{}^4$$

Due to the size distribution in exponential manner (integration of precip for whole size results in constant), we can apply the bulk property microphysics terms.

48

7.4 Bulk Method : 1-Moment versus 2-Moment

Mixing Ratio

(1-moment/ 2-moment scheme)

$$\left(\int \frac{dM(D_R)}{dt} dN_{DR} \right) / \rho = \frac{dq}{dt} (kgkg^{-1}s^{-1})$$

Number concentration

(2-moment scheme)

$$\left(\int \frac{d\,Pr\,ob(D_R)}{dt} dN_{DR} \right) = \frac{dN}{dt} (m^{-3}s^{-1})$$
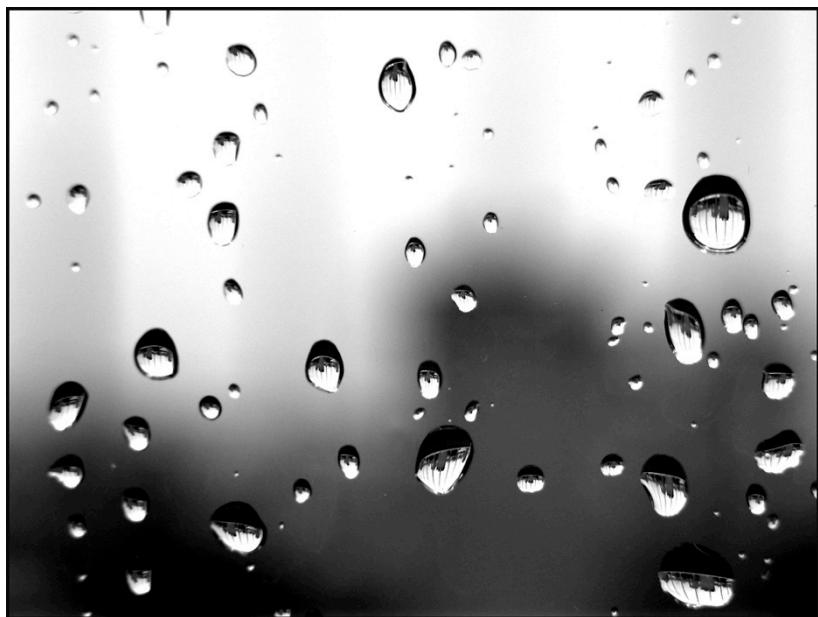
Single moment scheme

$$dN_{DR} = N_{0R} \exp(-\lambda_R D_R) dD_R$$

Double moment scheme

$$dN_{DR} = N_R \lambda_R^2 (N_R) D_R \exp(-\lambda_R D_R) dD_R$$

49

7.5 Bulk Method : 1-Moment (WSM) versus 2-Moment (WDM)

Cold rain processes :
(Hong et al. 2004; Hong and Lim 2006)

Ice q_I

Vapor q_V

Graupel q_G

Snow q_S
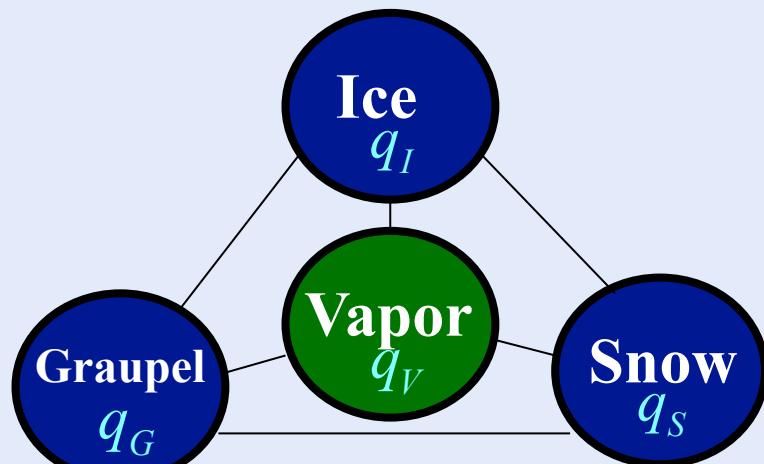
q for 4 hydrometeors will be predicted (Single Moment)

Warm rain processes :
(Khairoutdinov and Kogan 2000; Cohardt and Pinty 2000)

CCN N_{CCN} ← *"aerosol"*

Cloud water N_C / q_C

Vapor q_V

RAIN N_R / q_R
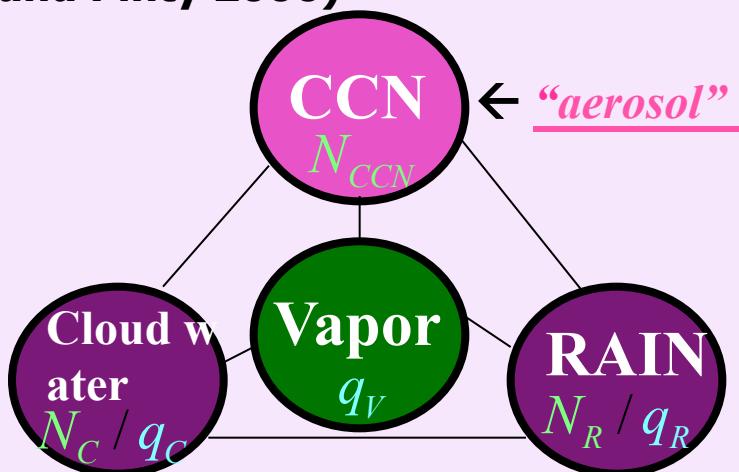
N,q for 2 hydrometeors will be predicted (Double Moment)

N: Cloud water, Rain, CCN

q: Cloud water, Rain, Ice, Snow, Graupel, Vapor

WDM6

(Lim and Hong, 2010)

7.6 WDM6 code

** Warm rain processes** (Lim and Hong 2010)

```
! warm rain processes
!
! - follows the double-moment processes in Lim and Hong
!
!========================================================
!
    do k = kts, kte
        do i = its, ite
            supsat = max(q(i,k),qmin)-qs(i,k,1)
            satdt = supsat/dtcld
!-----------------------------------------------------
! praut: auto conversion rate from cloud to rain  [LH 9] [CP 17]
!        (QC->QR)
!-----------------------------------------------------
            lencon  = 2.7e-2*den(i,k)*qci(i,k,1)*(1.e20/16.*rslopec2(i,k)   &
                      *rslopec2(i,k)-0.4)
            lenconcr = max(1.2*lencon, qcrmin)
            if(avedia(i,k,1).gt.di15) then
            taucon = 3.7/den(i,k)/qci(i,k,1)/(0.5e6*rslopec(i,k)-7.5)
            praut(i,k) = lencon/taucon
            praut(i,k) = min(max(praut(i,k),0.),qci(i,k,1)/dtcld)
!-----------------------------------------------------
! nraut: auto conversion rate from cloud to rain [LH A6] [CP 18 & 19]
!        (NC->NR)
!-----------------------------------------------------
            nraut(i,k) = 3.5e9*den(i,k)*praut(i,k)
            if(qrs(i,k,1).gt.lenconcr)                                      &
            nraut(i,k) = ncr(i,k,3)/qrs(i,k,1)*praut(i,k)
            nraut(i,k) = min(nraut(i,k),ncr(i,k,2)/dtcld)
            endif
!-----------------------------------------------------
! pracw: accretion of cloud water by rain       [LH 10] [CP 22 & 23]
!        (QC->QR)
! nracw: accretion of cloud water by rain        [LH A9]
!        (NC->)
!-----------------------------------------------------
            if(qrs(i,k,1).ge.lenconcr) then
            if(avedia(i,k,2).ge.di100) then
            nracw(i,k) = min(ncrk1*ncr(i,k,2)*ncr(i,k,3)*(rslopec3(i,k)     &
                         + 24.*rslope3(i,k,1)),ncr(i,k,2)/dtcld)
            pracw(i,k) = min(pi/6.*(denr/den(i,k))*ncrk1*ncr(i,k,2)         &
                         *ncr(i,k,3)*rslopec3(i,k)*(2.*rslopec3(i,k)        &
                         + 24.*rslope3(i,k,1)),qci(i,k,1)/dtcld)
            else
            nracw(i,k) = min(ncrk2*ncr(i,k,2)*ncr(i,k,3)*(2.*rslopec3(i,k)  &
                         *rslopec3(i,k)+5040.*rslope3(i,k,1)                &
                         *rslope3(i,k,1)),ncr(i,k,2)/dtcld)
            pracw(i,k) = min(pi/6.*(denr/den(i,k))*ncrk2*ncr(i,k,2)         &
                         *ncr(i,k,3)*rslopec3(i,k)*(6.*rslopec3(i,k)        &
                         *rslopec3(i,k)+5040.*rslope3(i,k,1)*rslope3(i,k,1))&
                         ,qci(i,k,1)/dtcld)
            endif
            endif
```

*Auto conversion from cloud to rain [C→R]

$$\text{Praut [kgkg}^{-1}\text{s}^{-1}] = L/\tau$$

$$L = 2.7\times10^{-2}\rho_a q_C\left(\frac{10^{20}}{16\lambda_C^4}-0.4\right)$$

$$\tau = 3.7\frac{1}{\rho_a q_C}\left(\frac{0.5\times10^6}{\lambda_C}-7.5\right)^{-1}$$

$$\text{Nraut[m}^{-3}\text{s}^{-1}] = 3.5\times10^9\frac{\rho_a L}{\tau}$$

*Accretion of cloud water by rain [C→R]

$D_R \geq 100\ \mu m$

$$\text{Pracw [kgkg}^{-1}\text{s}^{-1}] = \frac{\pi}{6}\frac{\rho_W}{\rho_a}K_1\frac{N_C N_R}{\lambda_C^3}\left\{\frac{2}{\lambda_C^3}+\frac{24}{\lambda_R^3}\right\}$$

$$\text{Nracw[m}^{-3}\text{s}^{-1}] = -K_1 N_C N_R\left\{\frac{1}{\lambda_C^3}+\frac{24}{\lambda_R^3}\right\}$$

$D_R < 100\ \mu m$

$$\text{Pracw [kgkg}^{-1}\text{s}^{-1}] = \frac{\pi}{6}\frac{\rho_W}{\rho_a}K_2\frac{N_C N_R}{\lambda_C^3}\left\{\frac{6}{\lambda_C^6}+\frac{5040}{\lambda_R^6}\right\}$$

$$\text{Nracw[m}^{-3}\text{s}^{-1}] = -K_2 N_C N_R\left\{\frac{2}{\lambda_C^6}+\frac{5040}{\lambda_R^6}\right\}$$

Resolution Dependency

Cut-off horizontal grid length: current status in research communities

- PBL : ~50 m (Mirocha, 2008 WRF workshop)
- GWDO : ~ 3 or 1 km (hydrostatic approximation)
- GWDC: ~ 3 or 1 km (go with CP)
- Cumulus parameterization : ~ 3 or 1 km (cloud resolving scale)

Gray-zone : partly resolved and partly parameterized
- CPS (1 km~10 km) : Gerard, Grell and Freitas, Arakawa and Ming, Pan and Han, Kwon and Hong
- PBL (100 m~1 km) : Honnert, Boutle, Shin and Hong
- Other processes such as shallow convection may also consider gray-zone

CPS gray-zone issue : A heavy rainfall simulated by WRF at 3 km
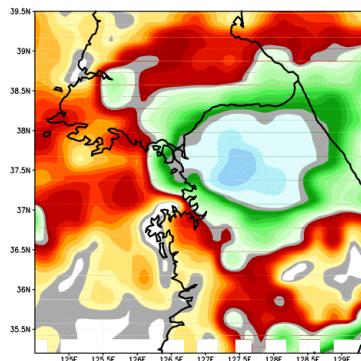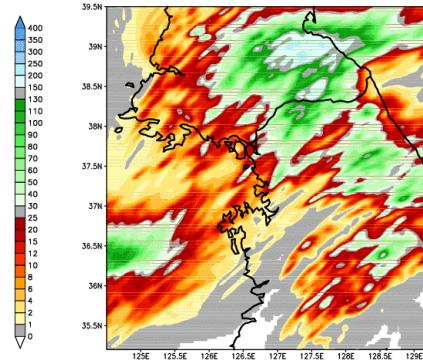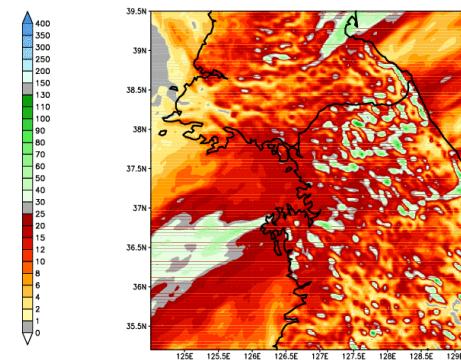
OBS   **No CPS**   **With CPS**

References

Anthes, R. A., 1977: A cumulus parameterization scheme utilizing a one-dimensional cloud model. *Mon. Wea. Rev.*, 105, 270-286. ♪

Arakawa, A., and W. H. Schubert, 1974: Interaction of a cumulus cloud ensemble with the large-scale environment, Part I. *J. Atmos. Sci.*, 31, 674-701.♪

Betts, A. K., 1986: A new convective adjustment scheme. Part I: Observational and theoretical basis. *Quart. J. Roy. Meteor. Soc.*, 112, 677 692.♪

Betts, A. K., and M. J. Miller, 1986: A new convective adjustment scheme. Part II: Single column tests using GATE wave, BOMEX, ATEX and arctic air-mass data sets. *Quart. J. Roy. Meteor. Soc.*, 112, 693-709. ♪

Charron, M., and E. Manzini, 2002: Gravity waves from fronts: Parameterization and middle atmosphere response in a general circulation model. *J. Atmos. Sci*., 59, 923–941.♪

Chen, F., and J. Dudhia, 2001: Coupling an advanced land-surface/hydrology model with the Penn State/NCAR MM5 modeling system. Part I: Model description and implementation. *Mon. Wea. Rev.*, 129, 569-585.♪

Choi, H.-J., and H.-Y. Chun, 2011: Momentum flux spectrum of convective gravity waves. Part I: An update of a parameterization using mesoscale simulations. *J. Atmos. Sci.*, 68, 739–759.

Choi, H.-j., S.-Y. Hong, 2015: An updated subgrid orographic parameterization for global atmospheric forecast models. J. Geophys. Res.: Atmospheres, 120, doi:10.1002/2015JD024230.♪

Chun, H.-Y., and J.-J. Baik, 1998: Momentum flux by thermally induced internal gravity waves and its approximation for large-scale models. Journal of the Atmospheric Sciences, 55, 3299-3310.♪

Chun, H. Y., and J. J. Baik, 2002: An updated parameterization of convectively forced gravity wave drag for use in large-scale models. *J. Atmos. sci.*, 59, 1006-1017.♪

Cohard, J.-M., and J.-P. Pinty, 2000: A comprehensive two-moment warm microphysical bulk scheme. I: Description and tests. *Quart. J. Roy. Meteor. Soc.*, 126, 1815-1842.

Dudhia, J., 1989: Numerical Study of Convection Observed during the Winter Monsoon Experiment Using a Mesoscale Two-Dimensional Model. *J. Atmos. Sci.*, 46, 3077–3107♪

Dyer, A. J., and B. B. Hicks, 1970: Flux-gradient relationships in the constant flux layer. *Quart. J. Roy. Meteor. Soc.*, 96, 715-721.♪

Emanual, K. A., 1991: A scheme for representing cumulus convection in large-scale models. *J. Atmos. Sci.*, 48, 2123-2335.♪

Gerard, L., J. M. Piriou, R. Brožková, J. F. Geleyn, and D. Banciu, 2009: Cloud and precipitation parameterization in a meso-gamma-scale operational weather prediction model. Mon. Wea. Rev., 137, 3960-3977.♪

Gregory, D., and P. R. Rowntree, 1990: A mass flux convection scheme with representation of cloud ensemble characteristics and stability-dependent closure. *Mon. Wea. Rev.*, 118, 1483-1506.♪

Grell, G. A. and Freitas, S. R.: A scale and aerosol aware stochastic convective parameterization for weather and air quality modeling. Atmos. Chem. Phys., 14, 5233-5250.♪

Grell, G. A., 1993: Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon. Wea. Rev.*, 121, 764-787. ♪

Gunn, K. L. S., and J. S. Marshall, 1958: The distribution with size of aggregate snowflakes. *J. Meteor.*, 15, 452-461.♪

Han, J., and H.-L. Pan, 2011: Revision of convection and vertical diffusion schemes in the NCEP global forecast system. *Wea. and Forecasting*, 26, 520-533.♪

Heymsfield, A. J., and C. M. R. Platt, 1984: A parameterization of the particle size spectrum of ice clouds in terms of the ambient temperature and the ice water content. *J. Atmos. Sci.*, 41, 846- 855.♪

Hong, S.-Y., and H.-L. Pan, 1996: Nonlocal boundary layer vertical diffusion in a Medium-Range Forecast model. *Mon. Wea. Rev.*, 124, 2322-2339.1♪

Hong, S.-Y., and J.-O. J. Lim, 2006: The WRF single-moment 6-class microphysics scheme (WSM6). *J. Korean Meteor. Soc.*, 42, 129-151.♪

Hong, S.-Y., J. Dudhia, and S.-H. Chen, 2004: A revised approach to ice microphysical processes for the bulk parameterization of clouds and precipitation. *Mon. Wea. Rev.*, 132, 103-120.♪

Jeon, J. H., S. Y., Hong, H. Y. Chun, and I. S. Song, 2010: Test of a convectively forced gravity wave drag parameterization in a general circulation model. *Asia-Pac. J. Atmos. Sci.*, 46, 1-10.♪

Johnson, R. H., 1976: The Role of Convective-Scale Precipitation Downdrafts in Cumulus and Synoptic-Scale Interactions. *J. Atmos. Sci.*, 33, 1890–1910.♪

Kain, J. S., 2004: The Kain-Fritsch convective parameterization : An update. *J. Appl. Meteor*, 43, 170-181.♪

Kang, H. S., and S.-Y. Hong, 2008: Sensitivity of the simulated East Asian summer monsoon climatology to four convective parameterization schemes. J. Geophys. Res.: Atmos. (1984-2012), 113(D15)♪

Kantha, L. H., 2003: On an Improved Model for the Turbulent PBL. *J. Atmos. Sci.*, 60, 2239–2246.♪

Khairoutdinov, M., and Y. Kogan, 2000: A new cloud physics parameterization in a large-eddy simulation model of marine stratocumulus. *Mon. Wea. Rev.*, 128, 229-243.♪

Kim, Y.-J., and A. Arakawa, 1995: Improvement of orographic gravity-wave parameterization using a mesoscale gravity-wave model. *J. Atmos. Sci.*, 52, 1875-1902.♪

Kim, Y.-J., and S.-Y. Hong, 2009: Interaction between the orography-induced gravity wave drag and boundary layer processes in a global atmospheric model. *Geophys. Res. Lett.*, 36, L12809, doi: 10.1029/2008GL037146.

Kim, Y.-J., and S.-Y. Hong, 2009: Interaction between the orography-induced gravity wave drag and boundary layer processes in a global atmospheric model. *Geophys. Res. Lett.*, 36, L12809, doi: 10.1029/2008GL037146.♪

Krishnamurti, T. N., L.-N. Simon, and R. J. Pasch, 1983: Cumulus parameterization and rainfall rates I. *Mon. Wea. Rev.*, 111, 815-4828.♪

♪

Krishnamurti, T. N., Y. Ramanathan, H. L. Pan, R. J. Pasch, and J. Molinari, 1980: Cumulus parameterization and rainfall rates I. *Mon. Wea. Rev.*, 108, 465-472.♪

Kuo, H.-L., 1965: On the formation and intensification of tropical cyclones through latent heat release by cumulus convection. *J. Atmos. Sci.*, 22, 40-63.

Kwon, Y.-C., and S.-Y. Hong, 2017 : A mass-flux cumulus parameterization scheme across gray-zone resolutions. *Mon. Wea. Rev., in press*♪

Lim, K.-S. S., and S.-Y. Hong, 2010: Development of an effective double-moment cloud microphysics scheme with prognostic cloud condensation nuclei (CCN) for weather and climate models. *Mon. Wea. Rev.*, 138, 1587-1612. ♪

Lock, A. P., A. R. Brown, M. R. Bush, G. M. Martin, and R. N. B. Smith, 2000: A new boundary layer mixing scheme. Part I: Scheme description and single-column model tests. *Mon. Wea. Rev.*, 128, 3187-3199. ♪

Louis, J. F., 1979: A parametric model of vertical eddy fluxes in the atmosphere. *Bound.-Layer Meteor.*, 17, 187-202.♪

Marshall, J. S., and W. MaK. Palmer, 1948: The distribution of raindrops with size. *J. Meteor*, 5, 165-166.♪

Mellor, G., and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems. *Rev. Geophys. Space Phys.,* 20, 851-875. ♪

Mirocha, J. D., J. K. Lundquist, F. K. Chow, and K. A. Lundquist, 2008: Demonstration of an improved subgrid stress closure for WRF. *The 8th WRF user's workshop*, Boulder, CO, NCAR, 5-4. ♪

Monin, A. S., and A. M. Obukhov, 1954: Basic laws of turbulent mixing in the surface layer of the atmosphere. *Trudy Geofiz. Inst. Akad. Nauk SSSR*, 24, 163-187.♪

Moorthi, S., and M. J. Suarez, 1992: Relaxed Arakawa-Schubert : A parameterization of moist convection for general circulation models. *Mon. Wea. Rev.*, 120, 978-1002.♪

Park, S., and C. S. Bretherton, 2009: The University of Washington shallow convection and moist turbulence schemes and their impact on climate simulations with the Community Atmosphere Model. *J. Climate*, 22, 3449-3469.♪

Richter, J. H., F. Sassi, and R. R. Garcia, 2010: Towards a physically based gravity wave source parameterization in a general circulation model. *J. Atmos. Sci.*, 67, 136–156.♪

Shin, H. H., and S.-Y. Hong, 2015: Representation of the Subgrid-Scale Turbulent Transport in Convective Boundary Layers at Gray-Zone Resolutions. DOI: 10.1175/MWR-D-14-00116.1♪

Slingo, J. M., 1987: The development and verification of a cloud prediction scheme for the ECMWF model. *Quart. J. Roy. Meteor. Soc.*, 113, 899-927.♪

Soares, P. M., P. M. Miranda, J. Teixeira, and A. P. Siebesma 2008: An Eddy-diffusivity/Mass-flux Boundary Layer Parameterization Based on the TKE Equation: a Dry Convection Case Study. *Física de la Tierra*, 19, 147-161.♪

Song, I.-S., and H.-Y. Chun, 2005: Momentum flux spectrum of convectively forced internal gravity waves and its application to gravity wave drag parameterization. Part I: *Theory. J. Atmos. Sci.*, 62, 107–124.♪

Song, I.-S., and H.-Y. Chun, 2008: A Lagrangian spectral parameterization of gravity wave drag induced by cumulus convection. *J. Atmos. Sci.*, 65, 1204–1224.♪

Stensrud, D. J., 2007: Parameterization schemes: keys to understanding numerical weather prediction models. Cambridge University Press.♪

Stull, R. B., 1988: An introduction to boundary layer meteorology. Kluwer Academic Publishers, The Netherlands, 666pp.♪

Tiedtke, M, 1989: A comprehensive mass flux scheme for cumulus parameterization in large-scale models. *Mon. Wea. Rev.*, 117, 1779-1800.♪

Tiedtke, M., 1983: The sensitivity of the time-mean large-scale flow to cumulus convection in the ECMWF model. *Proceedings of the ECMWF Workshop on Convection in Large-Scale Models*, Reading, United Kingdom, ECMWF, 297-316. ♪

Troen, I. B., and L. Mahrt, 1986: A simple model of the atmospheric boundary layer; sensitivity to surface evaporation. B*ound.-Layer Meteor*, 37, 129-148.♪

Yamada, T., and G. Mellor, 1975: A simulation of the Wangara atmospheric boundary layer data. *J. Atmos. Sci.*, 32, 2309-2329.♪

Thanks for your attention !

Modeling is to understand what is happening in nature !