

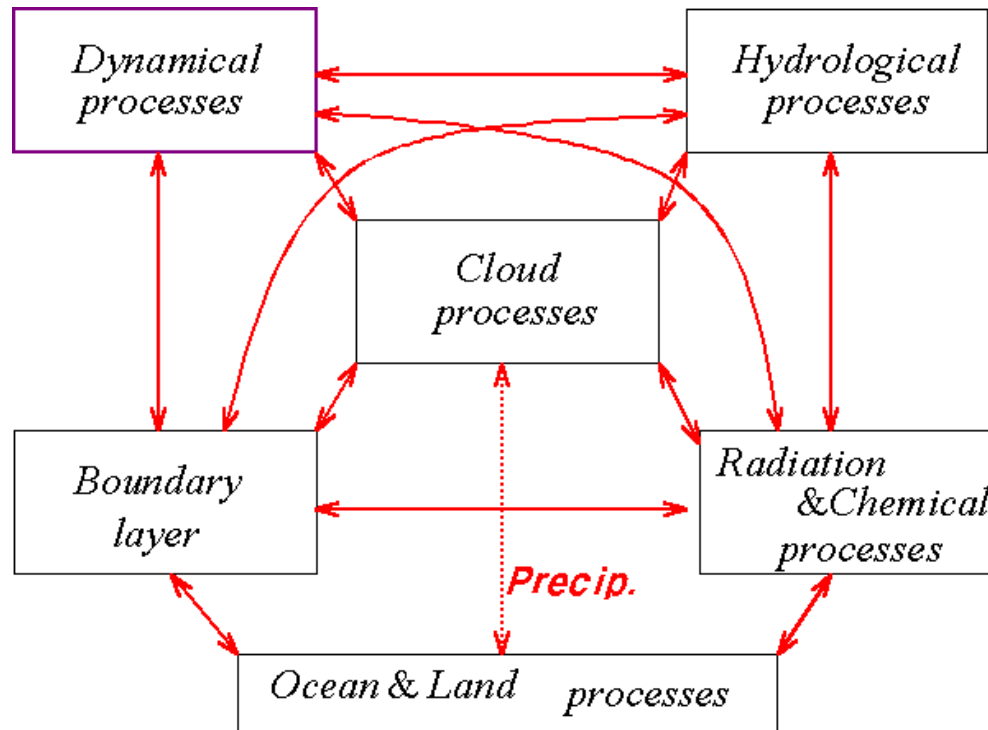
Overview of Physical Parameterizations

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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**

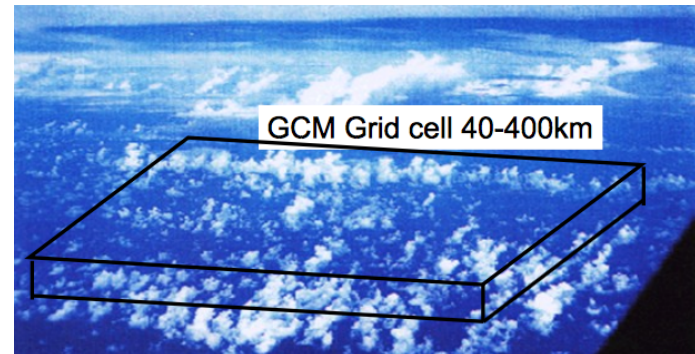
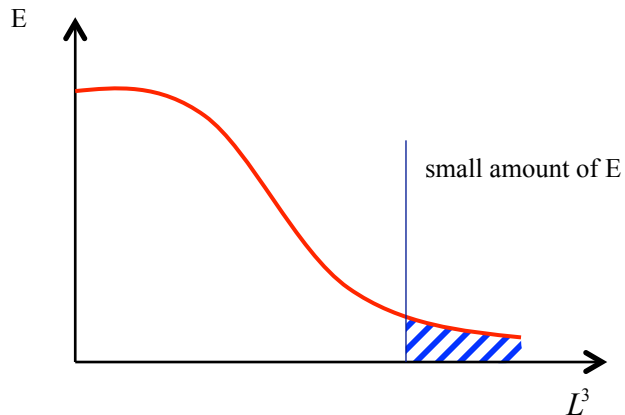
The formulation of physical process in terms of the model variables as parameters, i.e., constants or functional relations.

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)



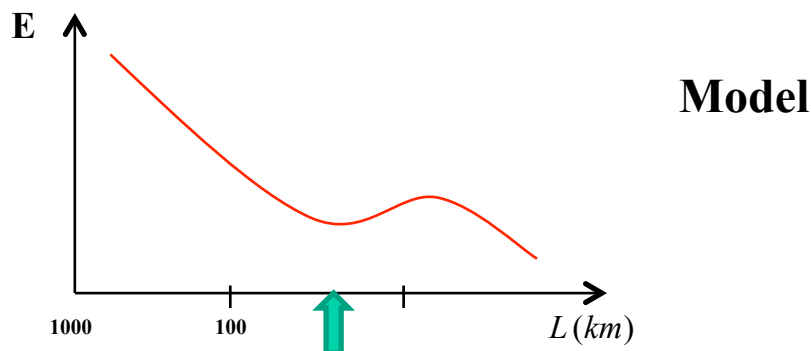
$\Delta x \rightarrow 0$, the energy dissipation takes place by molecular viscosity

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.”

1) Concept...continued

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

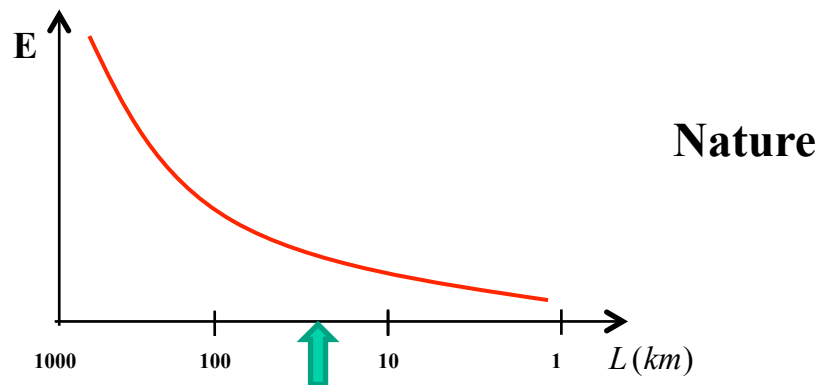


NWP model → Parameterization

← increasing scale ← hard truncation limit

where truncation limit ; spectral gap

Unfortunately, there is **no** spectral gap



2) Subgrid scale process & Reynolds averaging

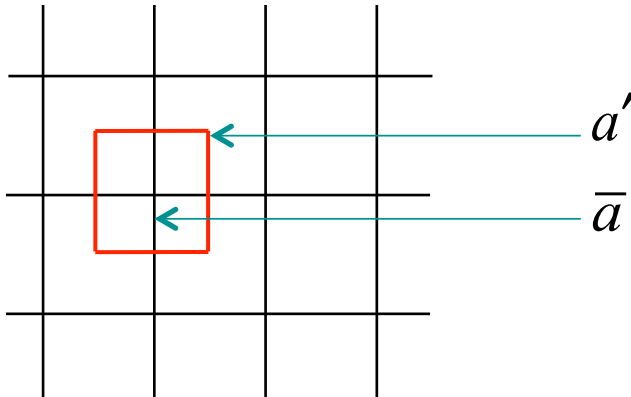
Consider prognostic water vapor equation

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

In the real atmosphere,

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

ρ' is neglected



2) Subgrid scale process & Reynolds averaging...continued

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

then eq.(1) becomes

$$\frac{\partial \rho \overline{q}}{\partial t} = - \underbrace{\frac{\partial \rho \overline{uq}}{\partial x} - \frac{\partial \rho \overline{vq}}{\partial y} - \frac{\partial \rho \overline{wq}}{\partial z}}_{\textcircled{1}} - \underbrace{\frac{\partial \rho \overline{u'q'}}{\partial x} - \frac{\partial \rho \overline{v'q'}}{\partial y} - \frac{\partial \rho \overline{w'q'}}{\partial z}}_{\textcircled{2}} + \rho E - \rho C \dots (2)$$

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

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

$$\frac{\partial \rho wq}{\partial t} = - \frac{\partial \rho uwq}{\partial x} + \dots$$

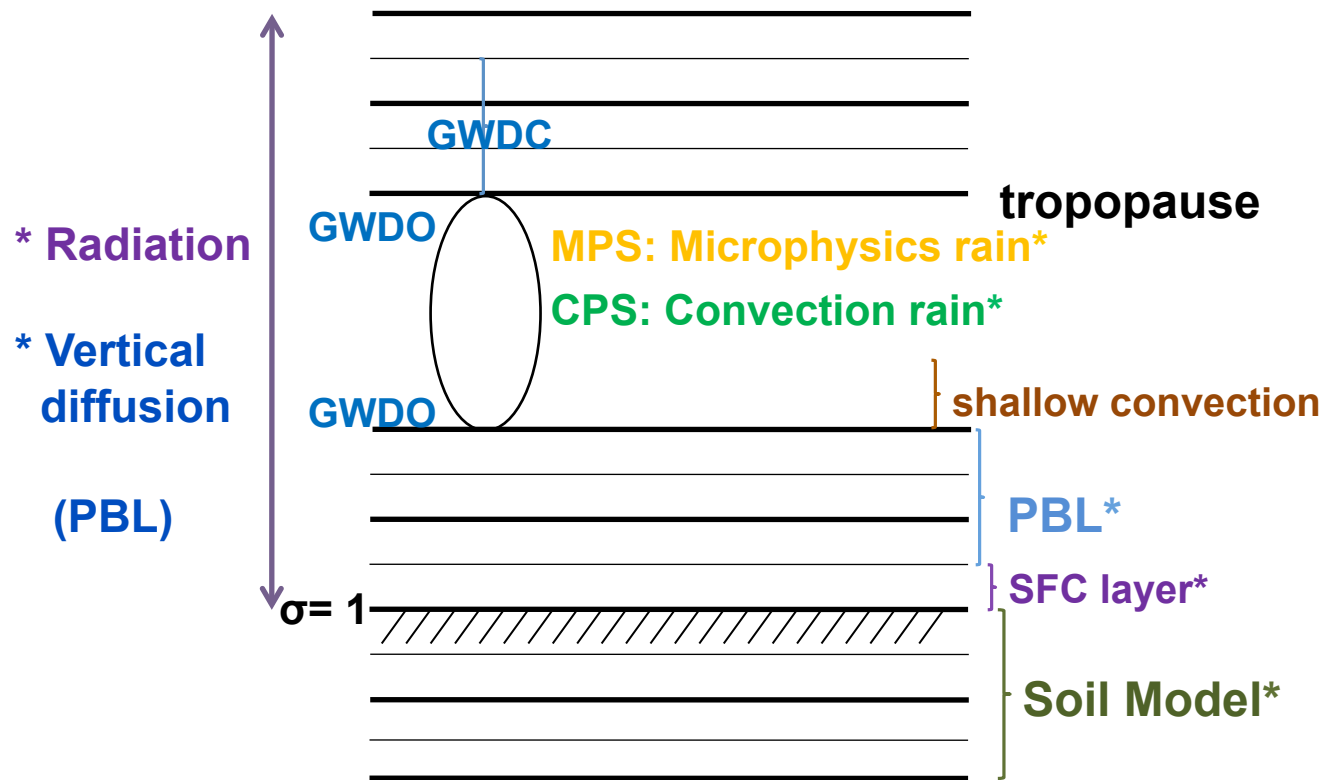
taking Reynolds averaging,

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

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

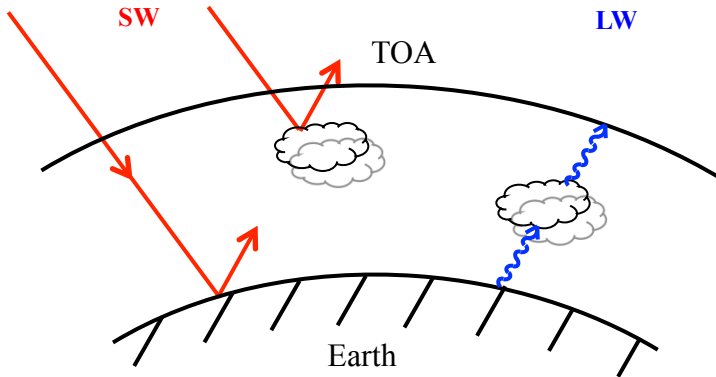
3) Schematic of physics algorithm : In modeled atmosphere : 7* ~10

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



1. Radiation

1.1 Concept



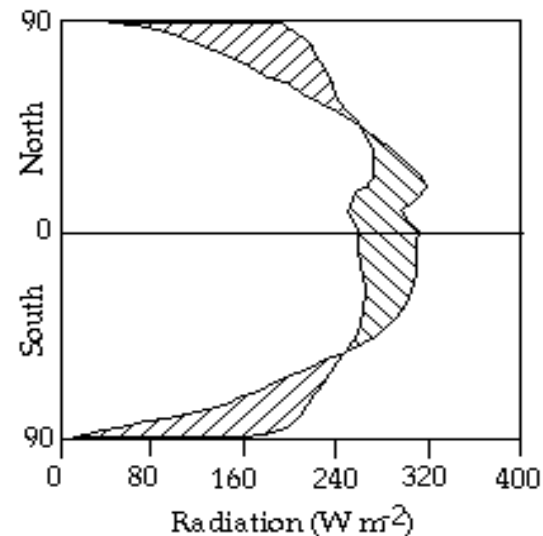
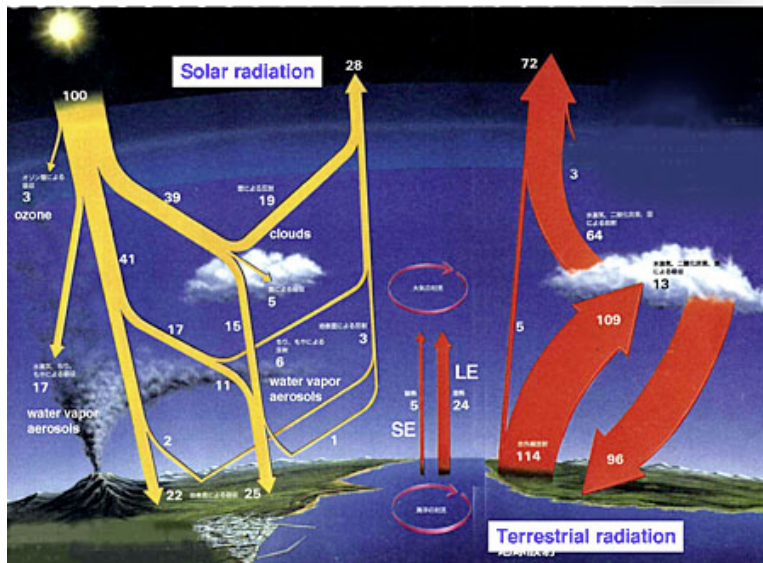
TOA : $S = 1360 \text{ } Wm^{-1}$

Mean Flux : $\frac{S}{4} = 340 \text{ } Wm^{-1} \rightarrow$ Energy source for Earth

30% : reflected from the atmosphere clouds

$\rightarrow$ Back to space by terrestrial infrared radiation

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

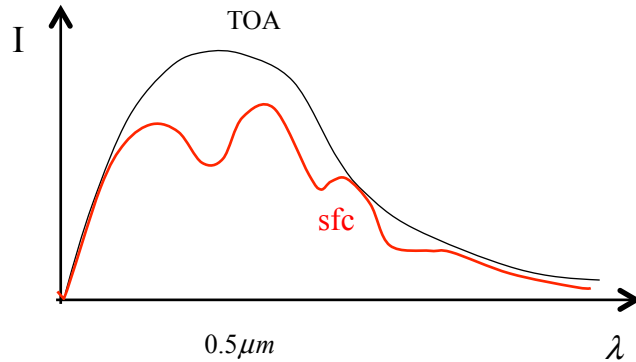


Energy loss

Energy gain

Energy loss

1.2 Solar radiative transfer



- At TOA,

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

(Insolation)

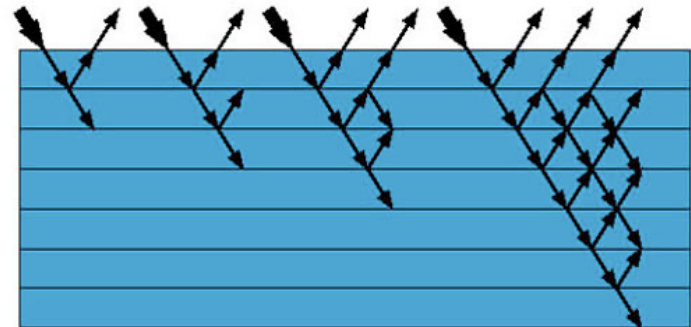
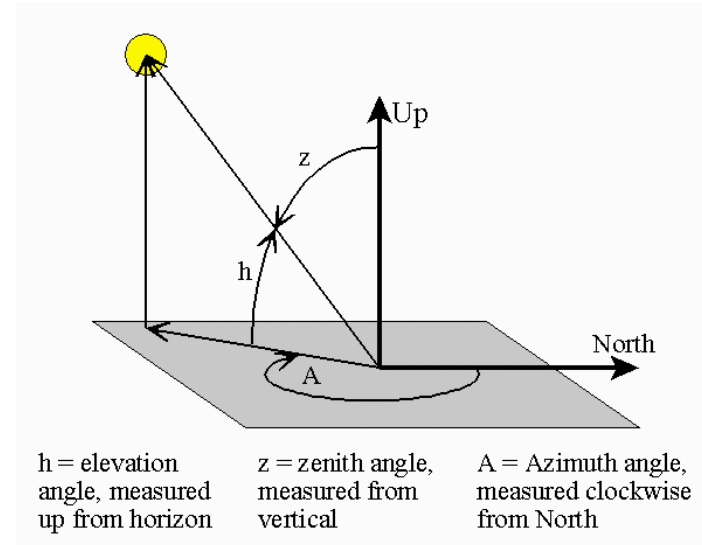
- Basic equations $\mu = \cos \theta$

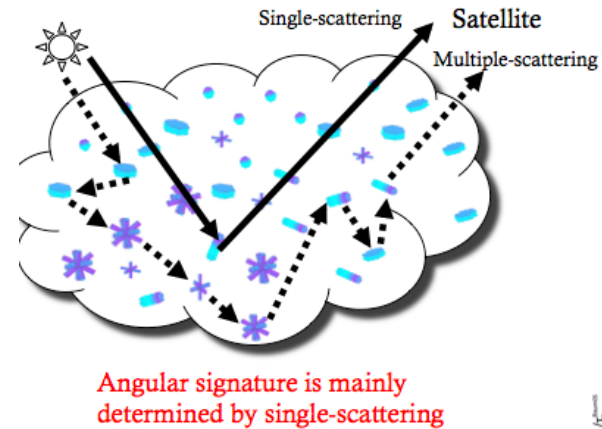
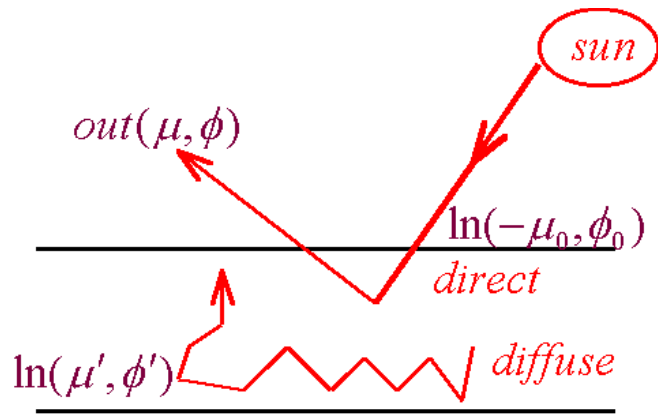
$$\mu \frac{dI(\tau, \mu, \phi)}{d\tau} = I(\tau, \mu, \phi) - J(\tau, \mu, \phi)$$

absorption source emission

$$d\tau = -k_v \rho_a dz \quad \tau(\text{optical depth}) = \int_z^{z_\infty} k_v(z') \rho_a(z') dz'$$

$$= \int_0^p k_v(p') q(p') \frac{dp'}{g}$$





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

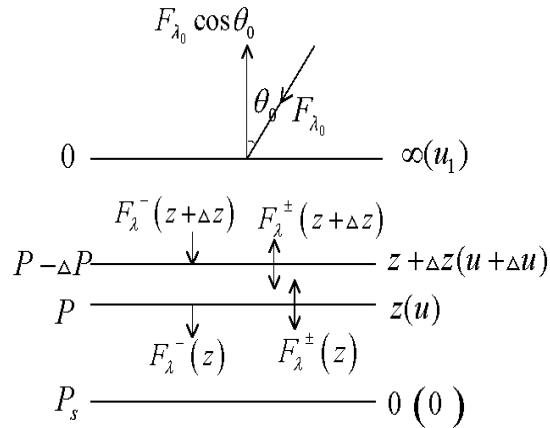
$$+ \frac{\tilde{\omega}}{4\pi} F_0 P(\mu, \phi; -\mu_0, \phi_0) e^{-\frac{\tau}{\mu_0}} [\text{single(direct) scattering}]$$

$$\left(\begin{array}{l} P : \text{Scattering phase function : redirects } (\mu', \phi') \rightarrow (\mu, \phi) \\ \tilde{\omega} = \frac{\sigma_s}{\sigma_e} : \text{Scattering albedo} \\ \text{scattering cross section / extinction (scattering + absorption) cross section} \end{array} \right.$$

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

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

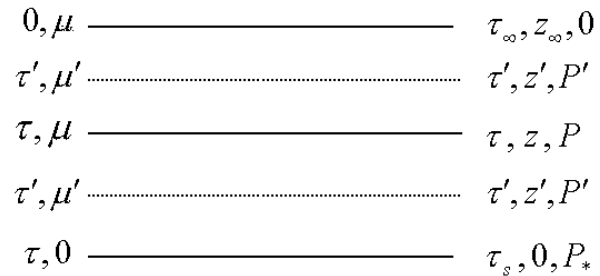
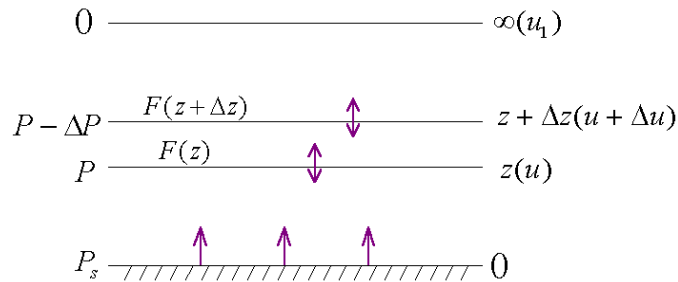
$$P(\cos\phi) = \sum_{l=0}^N \tilde{\omega}_l P_l(\cos\phi) \quad : \text{Legendre Polynomial}$$



Radiative transfer equation solver.

→ { Discrete - ordinates method
Two - Stream and Eddington's approximation
Delta - function adjustment and similarity principle
δ - Four stream approximation

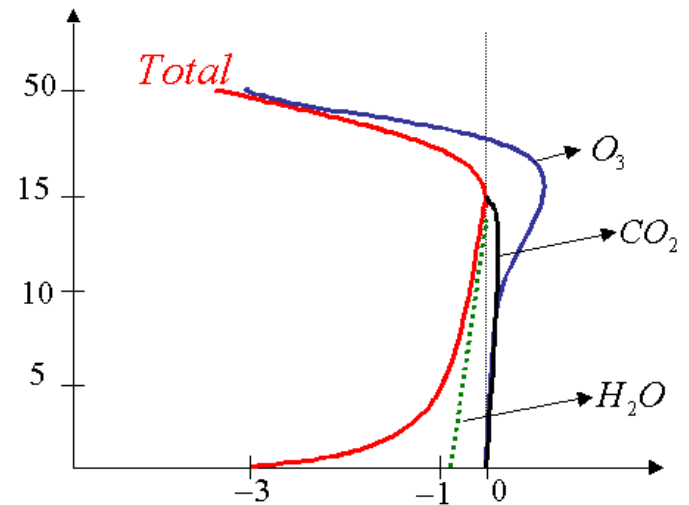
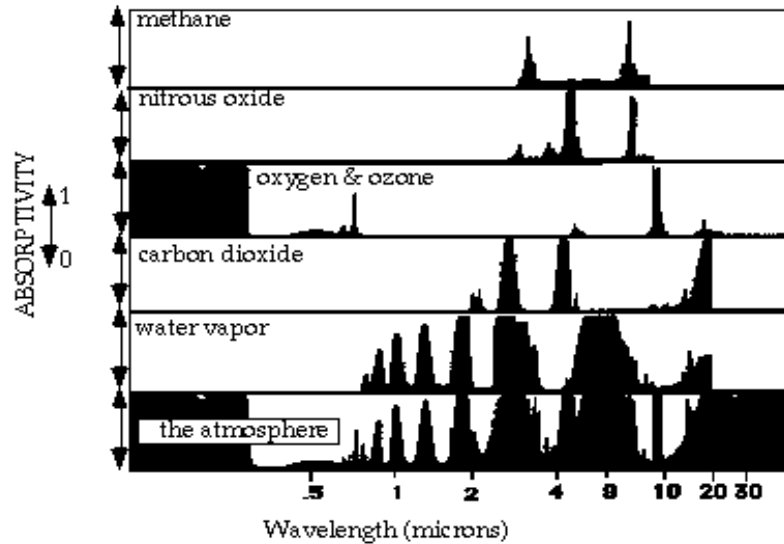
1.3 Terrestrial radiation



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

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

$$\left. \frac{\partial T}{\partial t} \right|_{IR} = -\frac{1}{c_p \rho} \frac{\Delta F}{\Delta P} = -\frac{g}{c_p} \frac{\Delta F}{\Delta u}$$



In spectral bands (monochromatic)

$$\uparrow \quad \mu \frac{dI_v(\tau, \mu)}{d\tau} = I_v(\tau, \mu) - B_v(T)$$

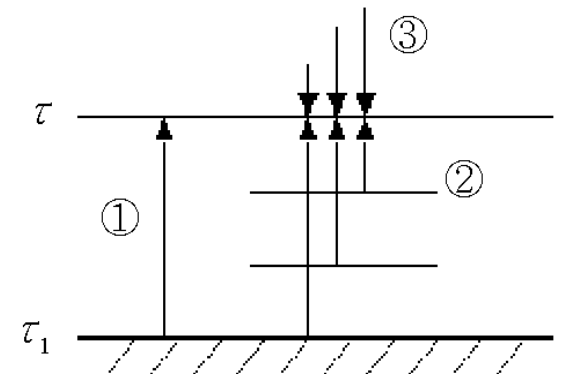
$$\downarrow \quad -\mu \frac{dI_v(\tau, -\mu)}{d\tau} = I_v(\tau, -\mu) - B_v(T)$$

$$\text{B.C.} \quad \begin{cases} \text{SFC } (\tau = \tau_1), I_v(\tau, \mu) = B_v(T_s) \\ \text{TOP } (\tau = 0), I_v(0, -\mu) = 0 \end{cases}$$

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

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

$$d\tau = -k_v \rho dz \quad \tau_1 = \int_0^{u_1} k_v du, \quad u_1 = \int_0^\infty \rho dz$$



LW is time consuming !

1.4 Cloud fraction

i) Conventional method (Slingo)

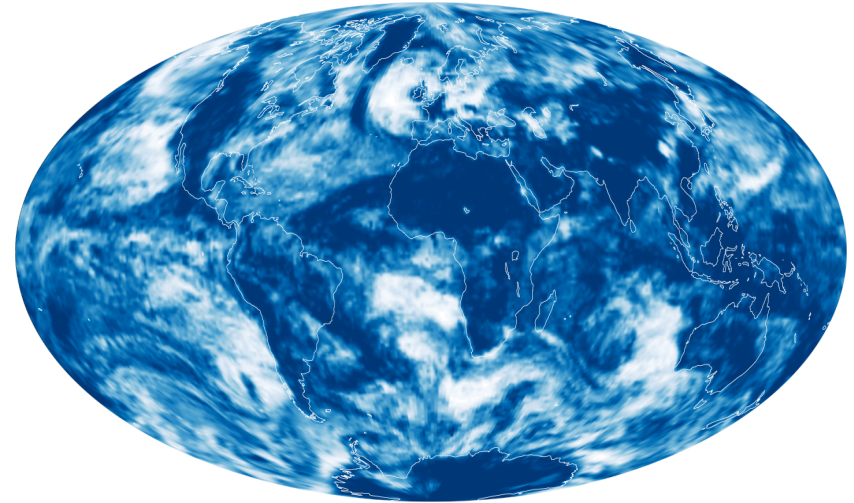
$$f = f_c + f_l$$

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

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

where RH_0 is the critical value of RH ,

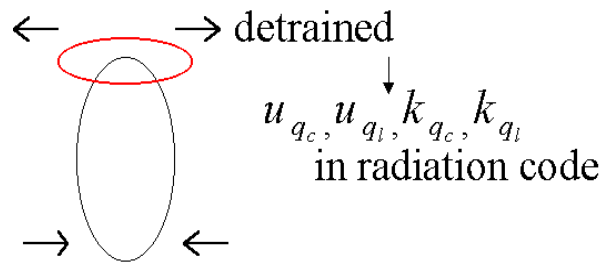
which is optimized based on observations



ii) Advanced method (Chou)

- inclusion of ice, liquid
- 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 parameterizations



f_l : use the hydrometeor information from microphysics routine, $q_c, q_s, q_i, \dots$

iii) Radiation properties

$$\tau_i^c = cwp \left[a_i + \frac{b_i}{r_{ei}} \right] f_{ice} \quad (\text{optical thickness})$$

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

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

$$f_i^c = (g_i)^2$$

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

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

(The effective optical thickness for each spectral band)

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

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

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

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

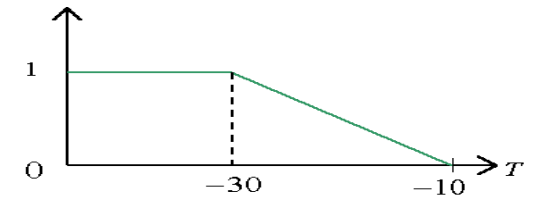
$$h_1 = a \ln(1.0 + \frac{b}{g} \int_{P_T}^{P_S} q dp)$$

- cloud droplet size,

$$r_{ee} \begin{cases} = 10 \mu m & \text{over ocean} \\ < 10 \mu m & \text{over land} \end{cases} : \text{warm clouds}$$

r_{ei} : $10 \mu m$ (low) ~ $30 \mu m$: (high) ice clouds

- ice fraction, f_{ice}



- For prognostic microphysics scheme,

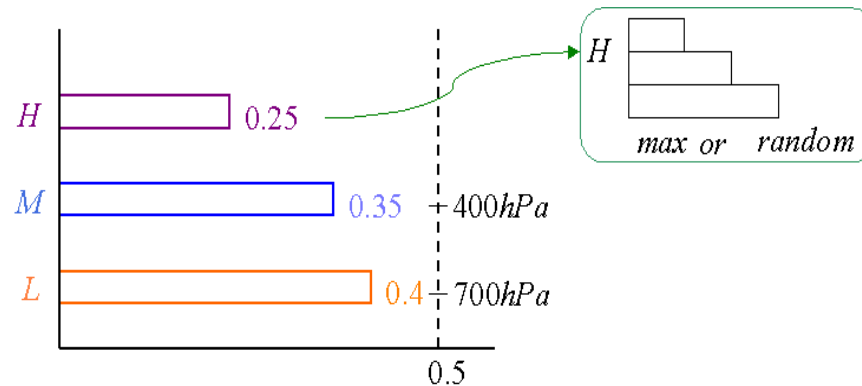
: Broadband radiation : Radiative properties are explicitly computed from prognostic water substances

: Simplified radiation : Dudhia (1989)

$$\alpha_p (\text{absorption coefficient}) = \frac{1.66}{2000} \left(\frac{\pi N_0}{\rho_{rs}^3} \right)^{\frac{1}{4}} m^2 g^{-1} = \begin{cases} 2.34 \times 10^{-3} m^2 g^{-1} & \text{for snow} \\ 0.33 \times 10^{-3} m^2 g^{-1} & \text{for rain} \end{cases}$$

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

iv) Cloud overlapping



Maximum overlapping : 0.4

Minimum overlapping : 1.0

Random overlapping : $H + (1-H)M + \{1-H-(1-H)M\}L = 0.6$

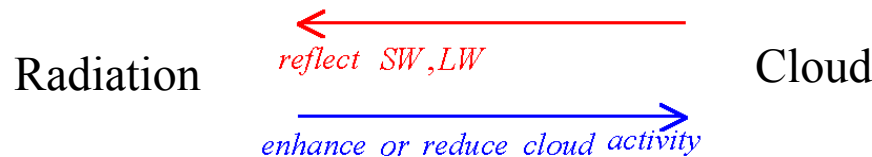
- Computation :

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



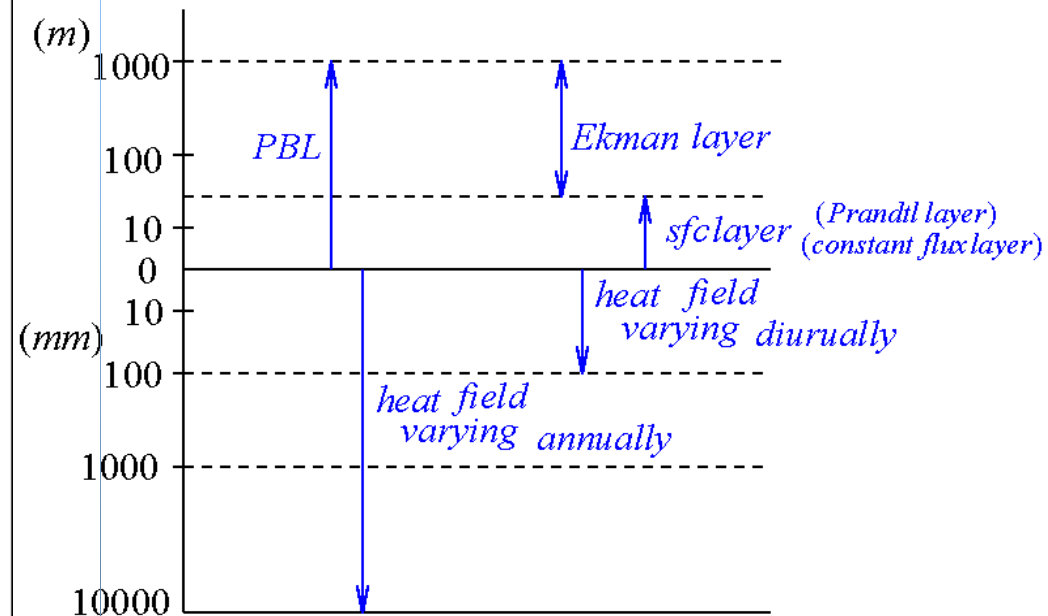
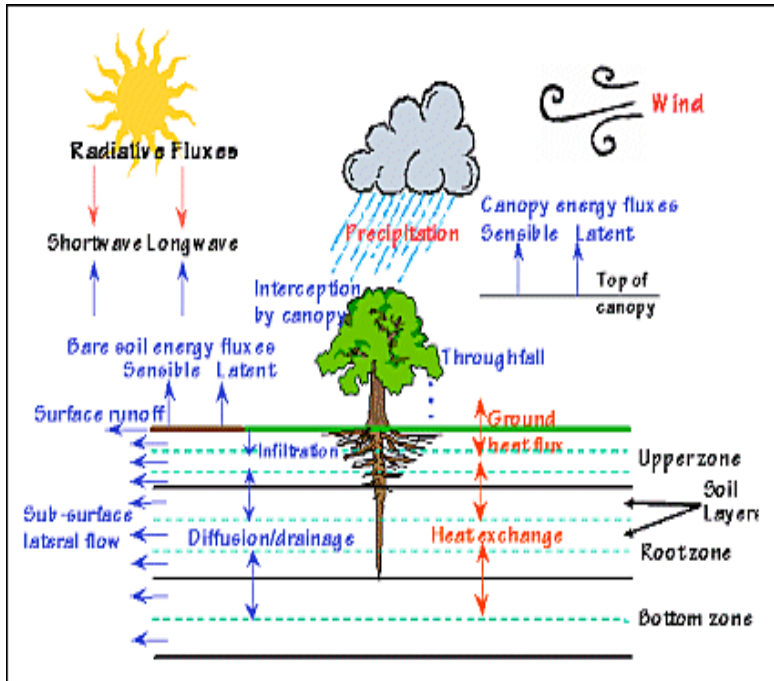
- Flux for each of $A_c, (1-A_c) \rightarrow$ summation

- Issues : $A_c = 0$ or 1 $\leftarrow$ in WRF versus partial cloudiness in GFS



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

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

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

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

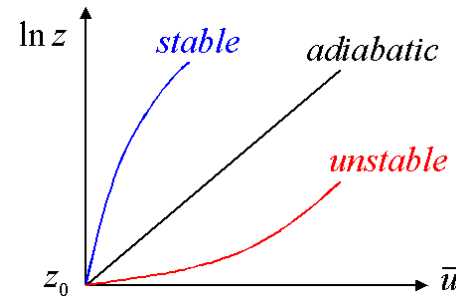
C_D, C_H : prescribed

= 0.01 over land, = 0.001 over water

2) Monin-Obukov similarity

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

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



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

Φ : curving factor

※ **Profile function** : ϕ_m and ϕ_t

Dyer and Hicks formula for similarity

- unstable ($L < 0$)

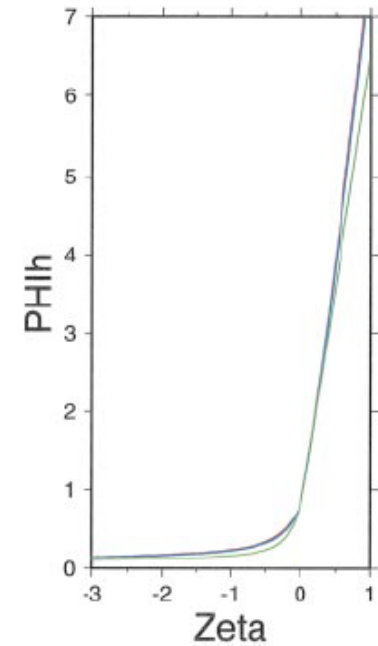
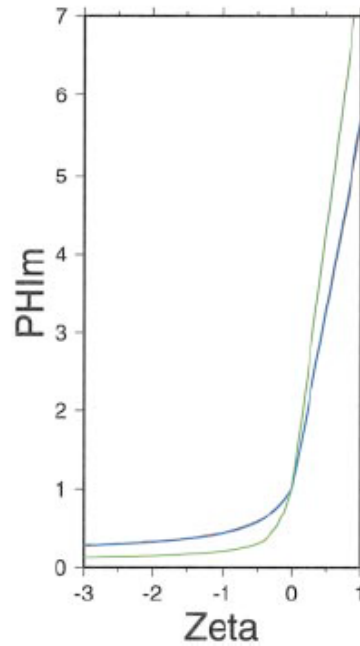
$$\phi_m = \left(1 - 16 \frac{0.1h}{L}\right)^{-\frac{1}{4}} \quad \text{for } u, v$$

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

- stable ($L > 0$)

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

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



**Kantha
(2003)**

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

$$\text{where } Ri = \frac{g}{\theta} \frac{\partial \theta}{\partial z} \left(\frac{\partial u}{\partial z}\right)^{-2}$$

※ **Useful relation** :

$$\text{Given the } F_m, F_H \quad C_D = k^2 / F_m^2, C_Q = C_H = k^2 / (F_m F_t) \quad u_* = kU / F_m$$

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

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

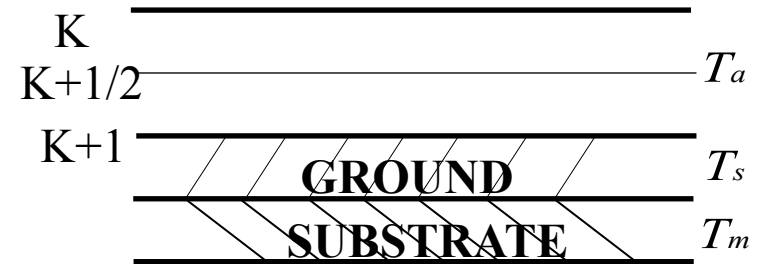
$$E_0 = -\rho L \overline{q'w'} = -\rho L C_q U \Delta q$$

2.3 Soil model

1) Slab model : force-restore method

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

$$\frac{\partial T_m}{\partial t} = \frac{1}{\tau} (T_s - T_m) : T_m, \text{ daily mean}$$



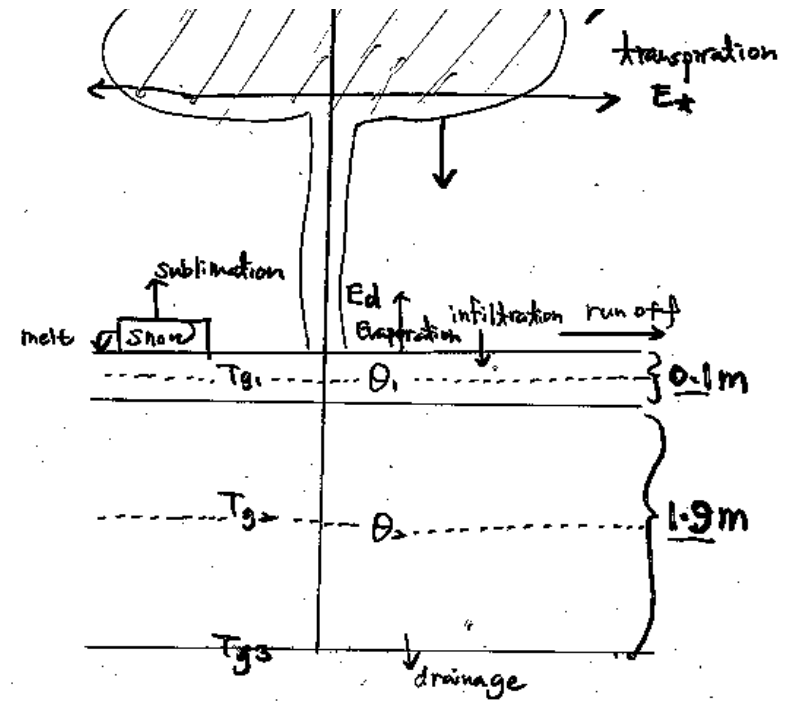
2) Multi-layer model : OSU method

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

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

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

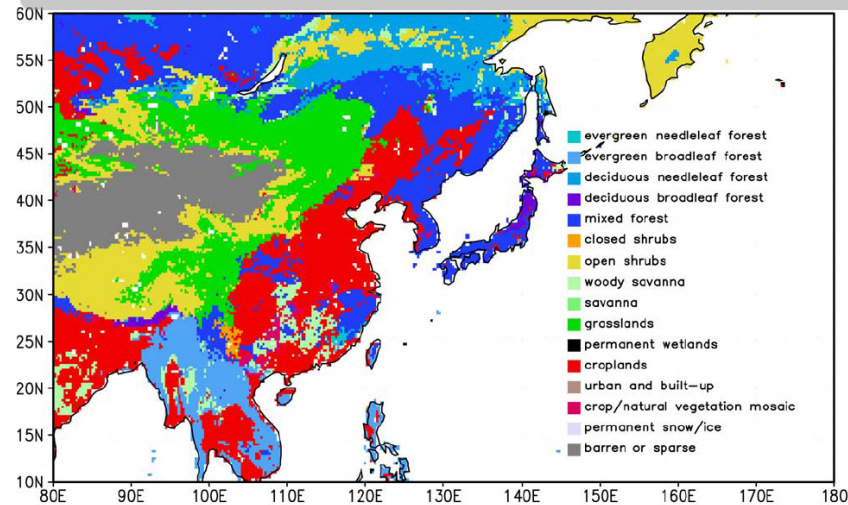
- NOAH, SIB, PLACE, VIC, CLM, etc



2.4 Vegetation type → z_0 , Albedo

Vegetation types

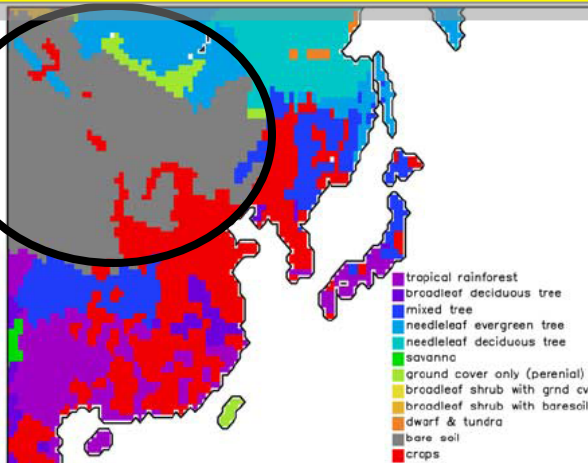
MODIS (satellite)



13 type data set
1 degree

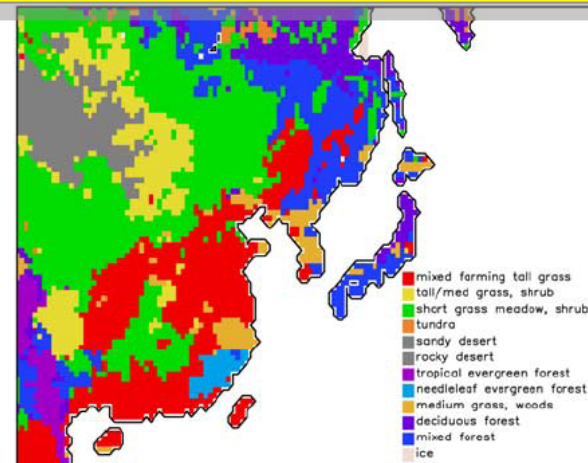
12 type data set
20 min

The Simple Biosphere model (SiB)



quite broad
desert region

United States Geological Survey's (USGS)



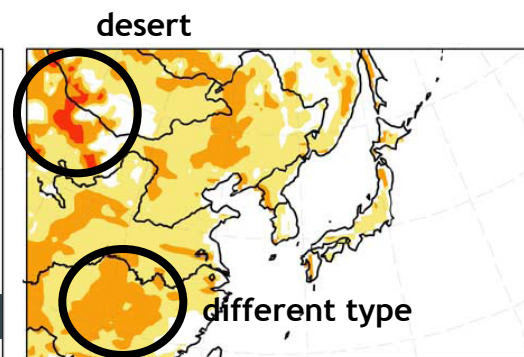
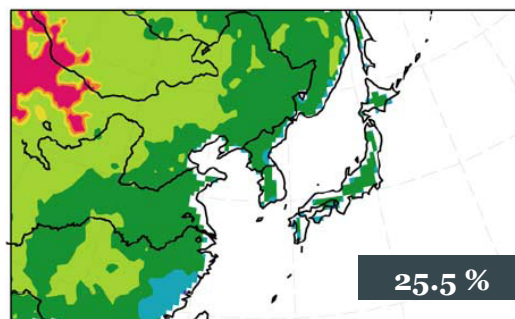
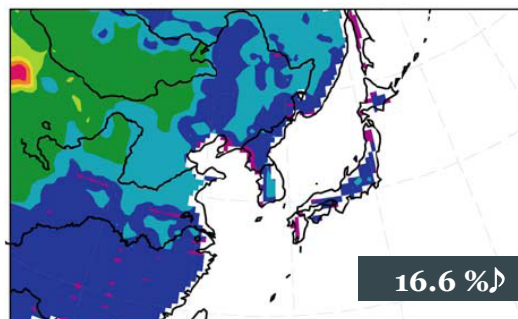
Albedo and roughness length (z_0)

Sib

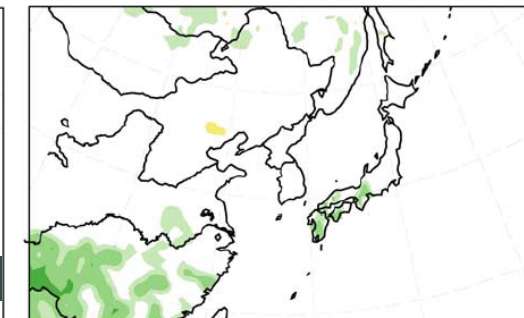
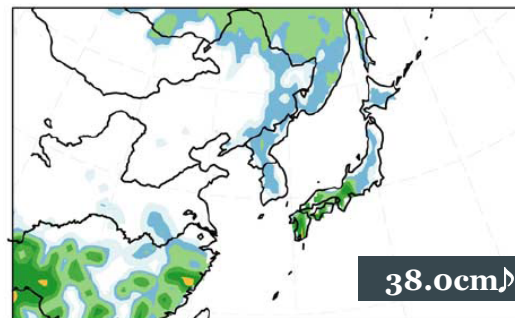
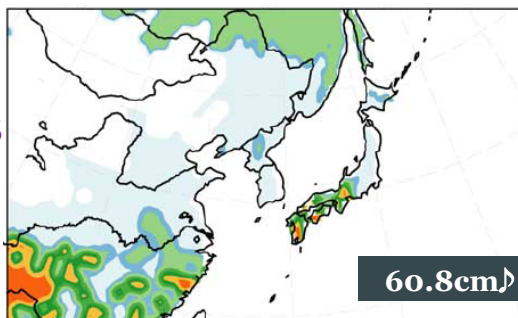
USGS

USGS-Sib

Albedo



Roughness
length

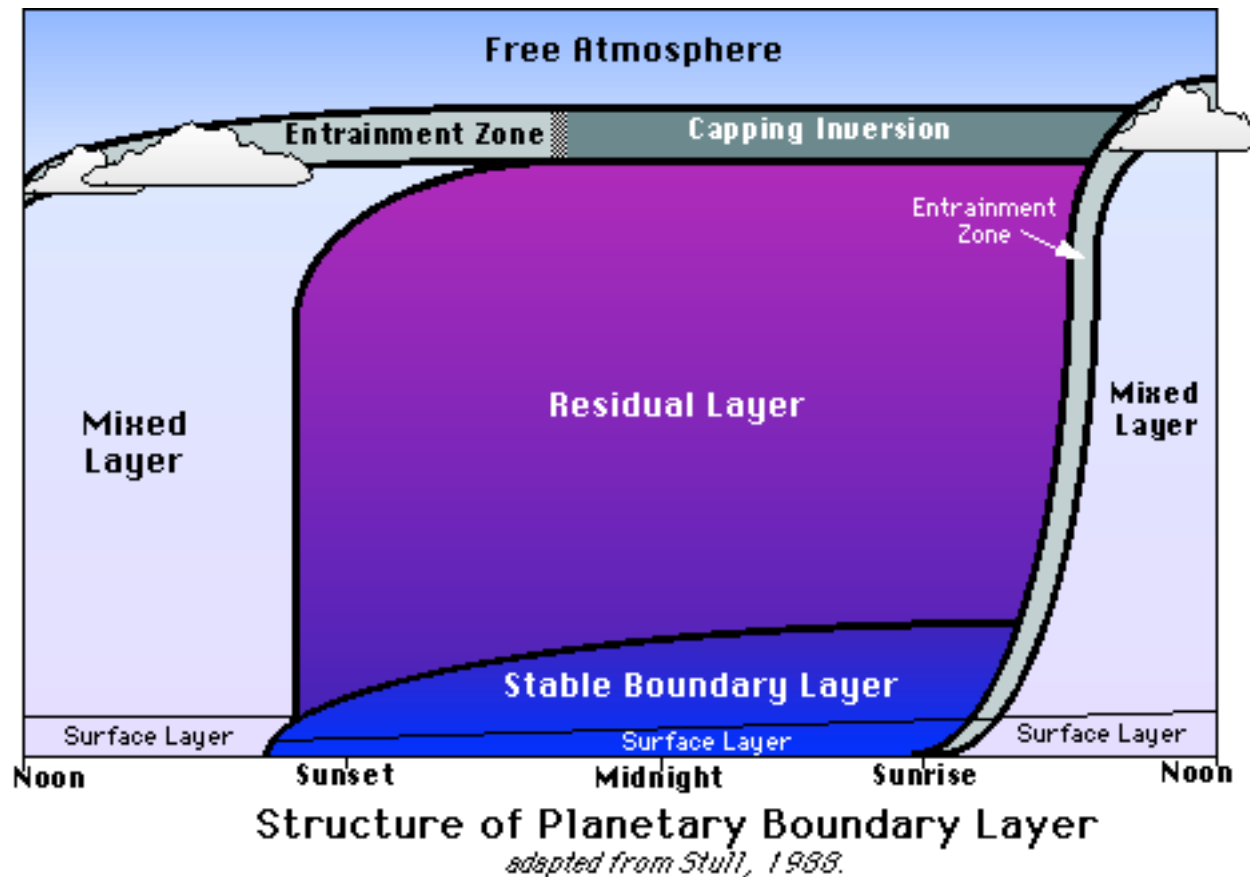


Much uncertainties in calibration/optimization !!!

3. Vertical diffusion (PBL)

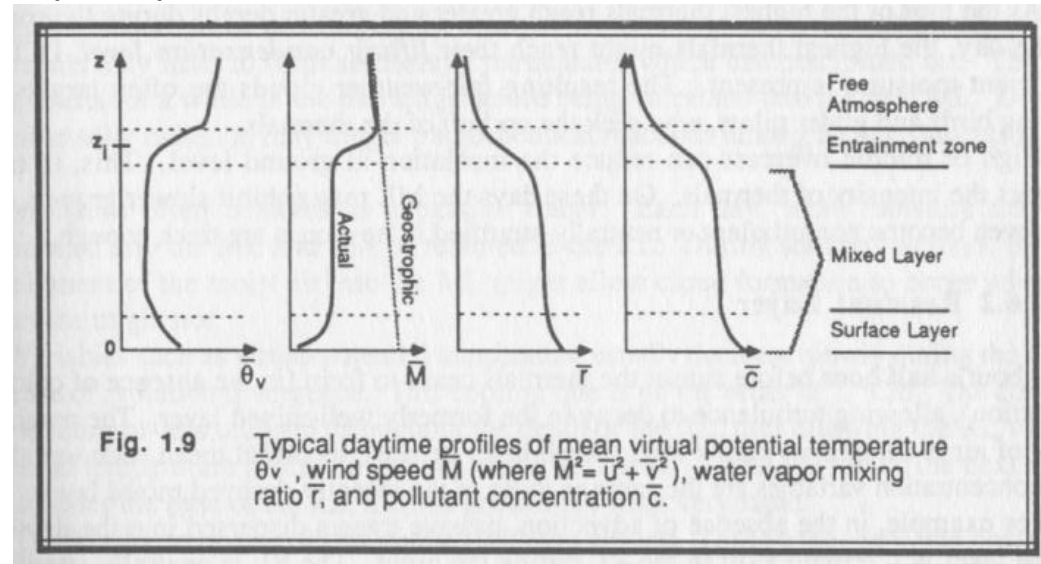
3.1 Concept

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

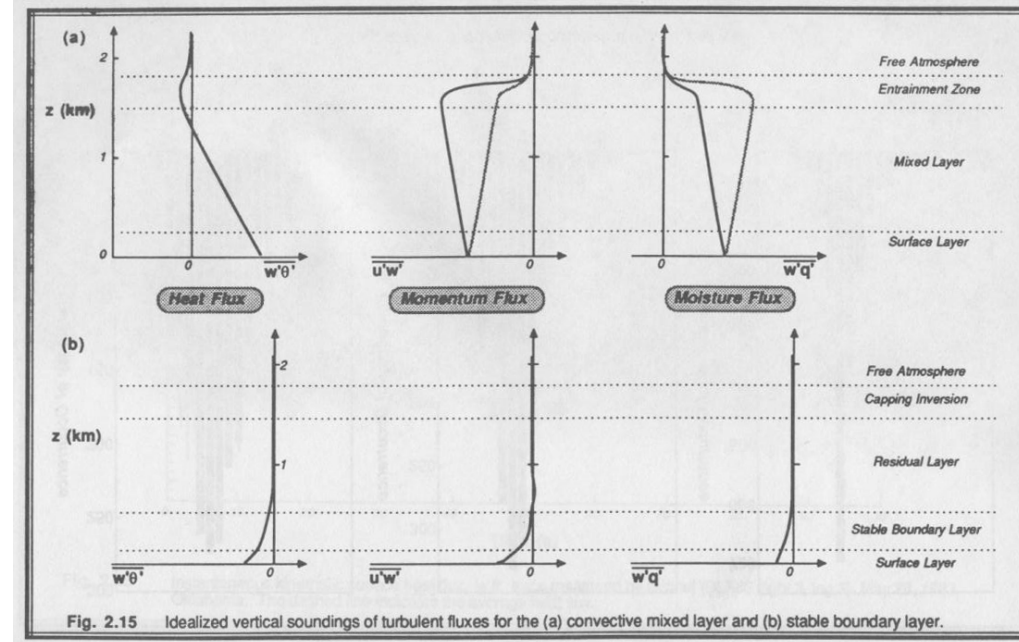


3.2 Planetary Boundary Layer Structure : schematic

Daytime profiles



Daytime flux profiles



Nighttime flux profiles

3.3 Classifications : how to determine, k_c

i) Local diffusion (Louis 1979)

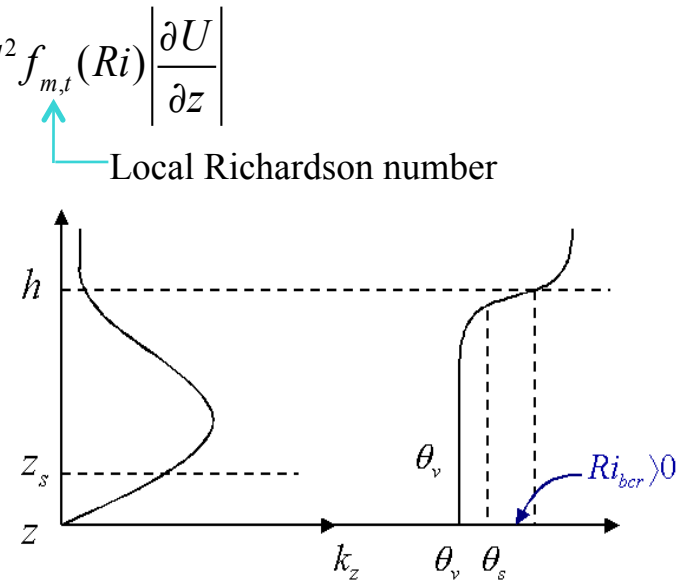
$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial z}(-\overline{w\bar{c}}) = \frac{\partial}{\partial z}(k_c \frac{\partial c}{\partial z}) \quad k_c : \text{ diffusivity, } k_m, k_t = l^2 f_{m,t}(Ri) \left| \frac{\partial U}{\partial z} \right|$$

ii) Nonlocal diffusion (Troen and Mahrt 1986)

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

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

$$\theta_s = \theta_{va} + \theta_T (= b \frac{(\overline{\theta_v' w'})_0}{w_s}), \quad w_s = u_* \phi_m^{-1}$$



iii) Eddy mass-flux diffusion (Siebesma and Teixeira 2000)

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

small eddies strong updrafts

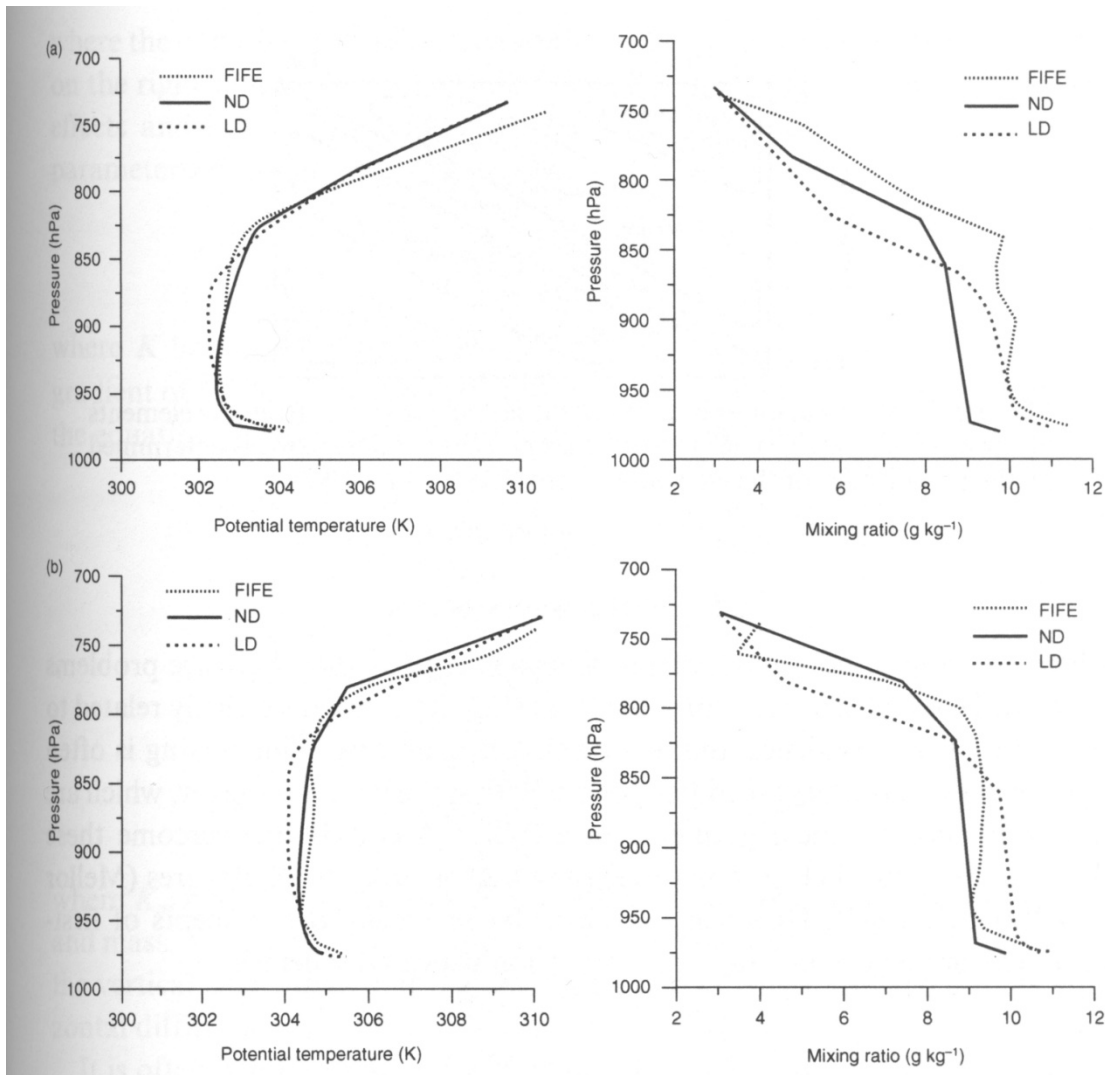
iv) TKE (Turbulent Kinetic Energy) diffusion (Mellor and Yamada 1982)

TKE equation :

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

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

3.4 Local versus nonlocal



Local scheme typically produces unstable mixed layer

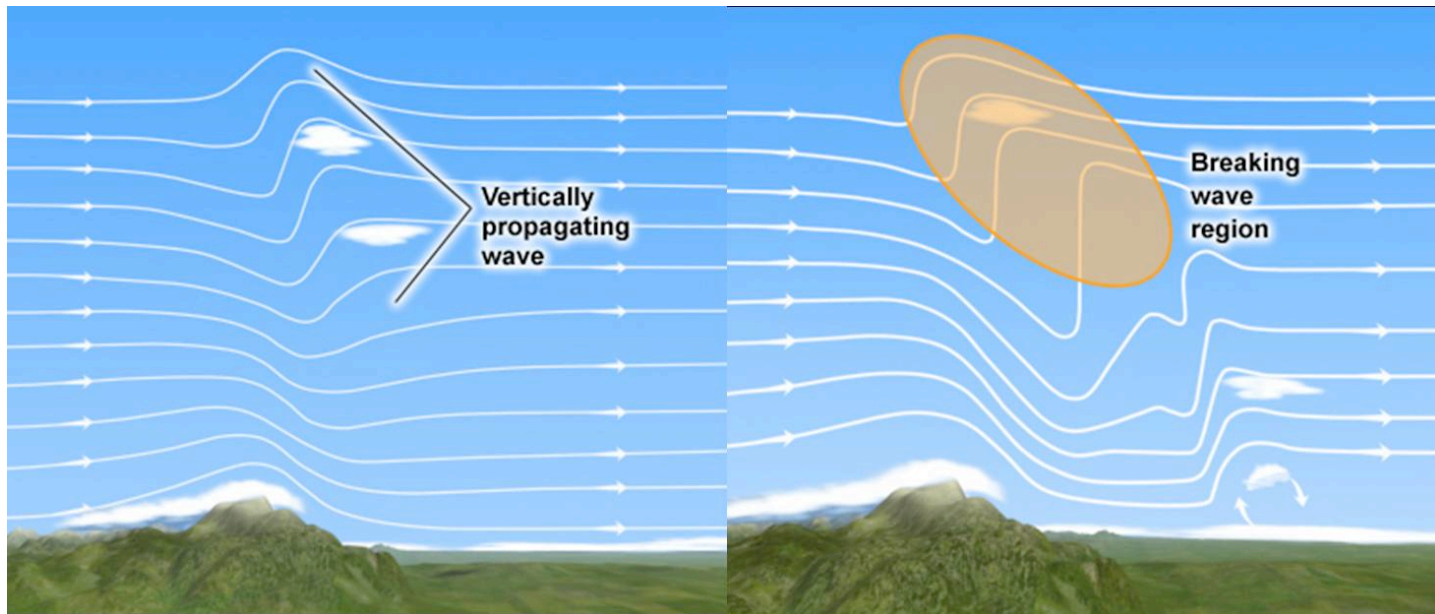
Hong and Pan (1996)

4. Gravity Wave Drag

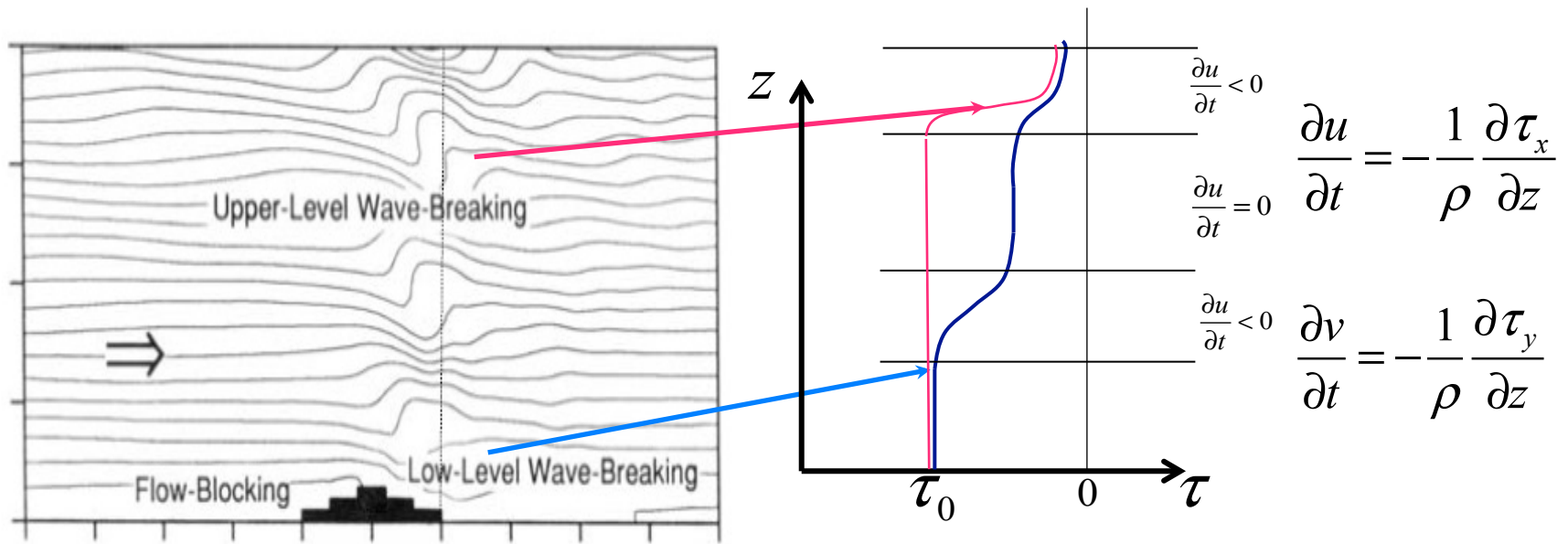
- GWDO : GWD induced by sub-grid scale orography
- GWDC : GWD induced by precipitating deep convection

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.



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



Stress at reference level :

$$\tau_0 = -E \frac{1}{\Delta x} \frac{\rho_0 U_0^3}{N_0} \frac{Fr^2}{Fr^2 + 0.5/OC}, \quad U_0 = \frac{1}{h} \int_{k=1}^{k=k_{pbl}} U dz$$

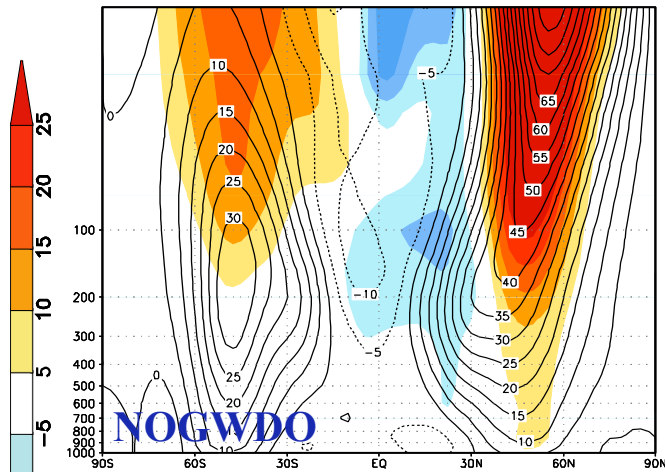
Reference level (KA95) : Max (2, KPBL)

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

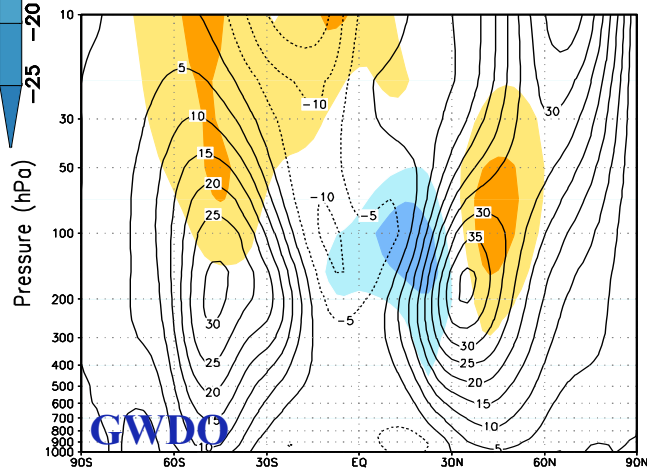
Advanced: the higher-moment orographic statistics-based wave- breaking mechanism using half-theory (Scorer parameter $\sim BVF^{**2} / U^{**2}$) and half-empiricism obtained from mesoscale mountain wave simulations, which works mainly in the lower atmosphere, together with flow blocking

4.3 Impact of GWDO

Zonal-averaged zonal wind (96/97 DJF)

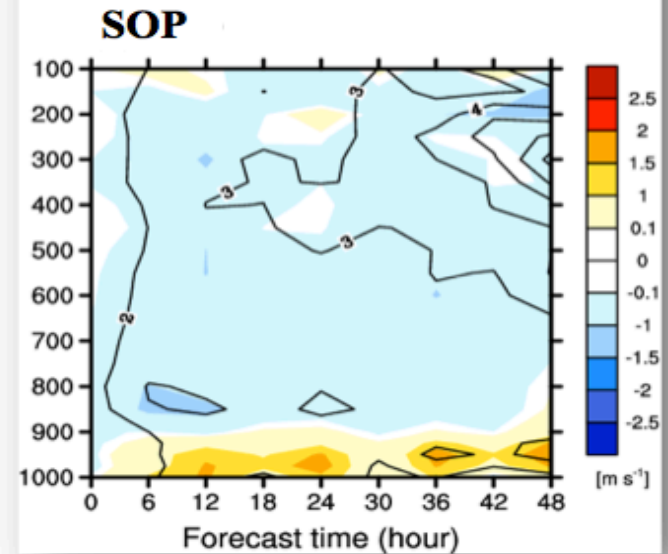
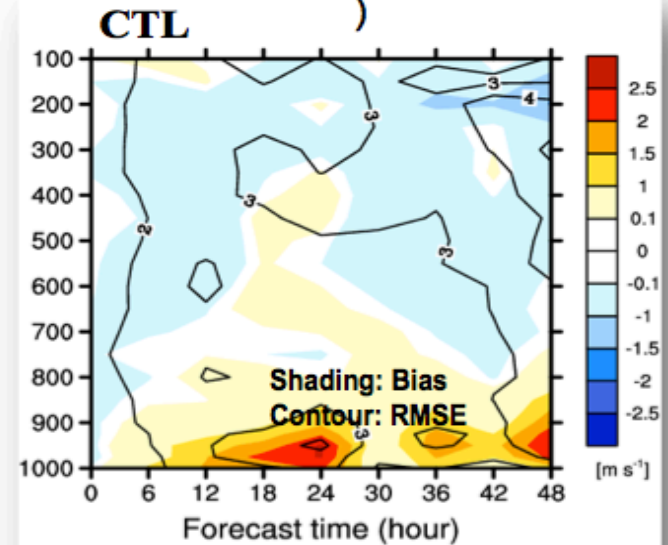


Contour : Zonal averaged zonal wind
Shaded: Deviations from the RA2



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

Wind speed (3-5 Jan. 2010)

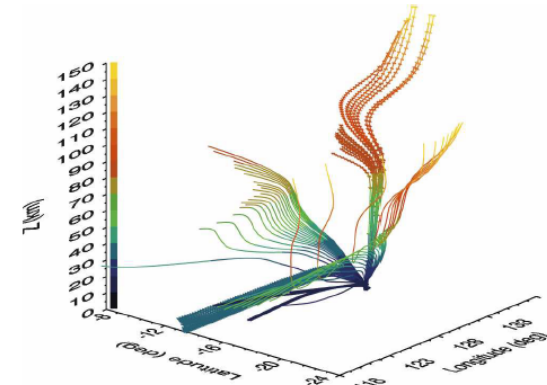
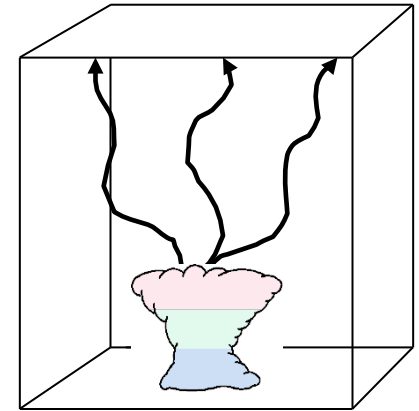


Flow blocking ➔ Improves the low-level winds (Choi and Hong, 2015)

4.4 Convective GWD (CGWD) or non-orographic GWD

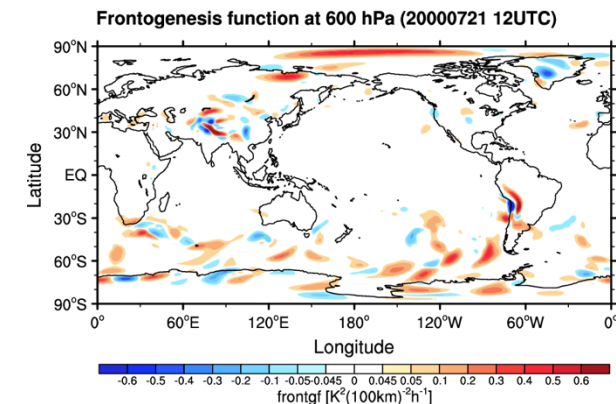
CGWD parameterizations

- 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

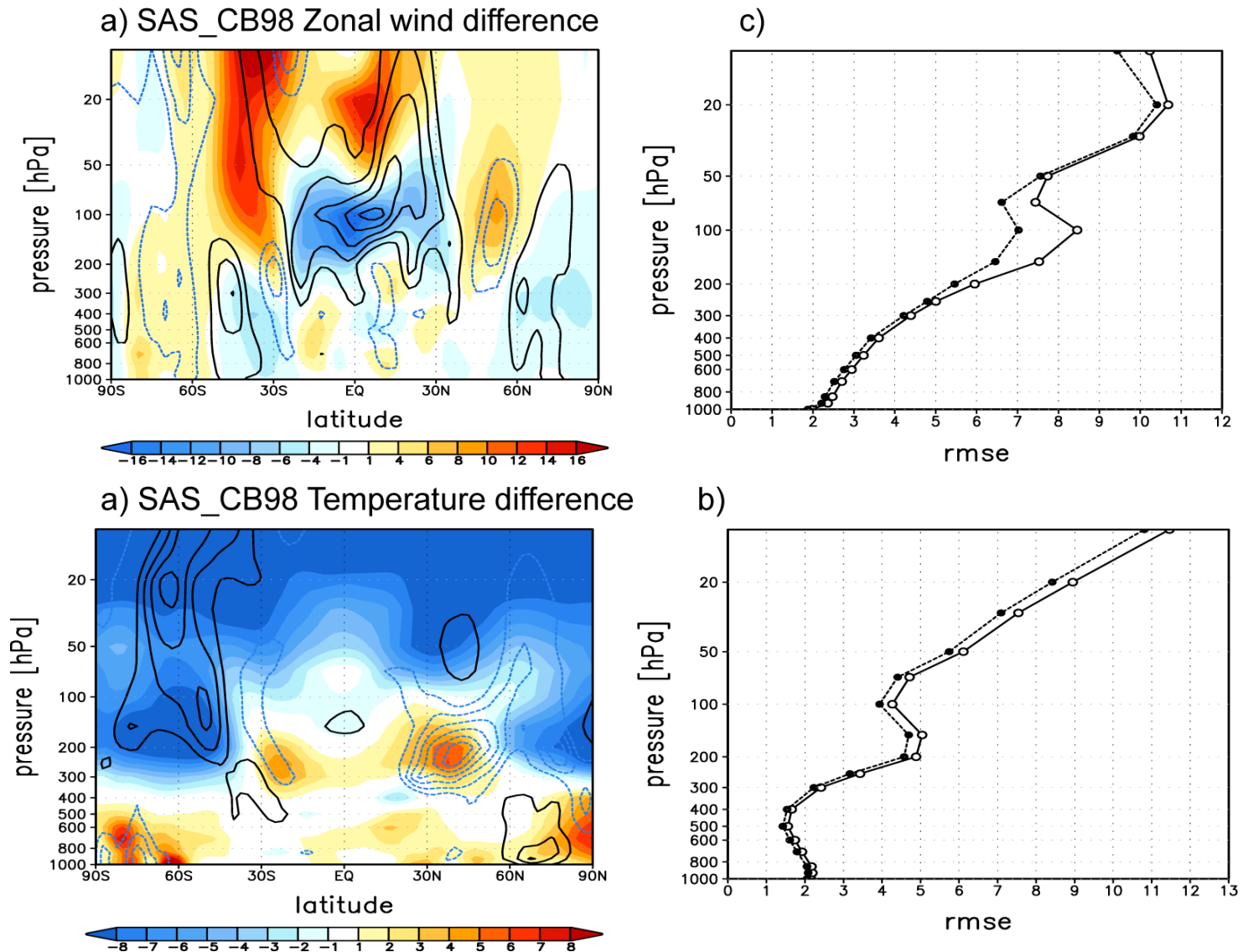


Jet/Front GWD parameterizations

- 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



4.5 Improvement by GWDC (Chun and Baik 1998, Jeon et al. 2010)



Wind and temperature RMSE are reduced in upper atmosphere

Precipitation Processes

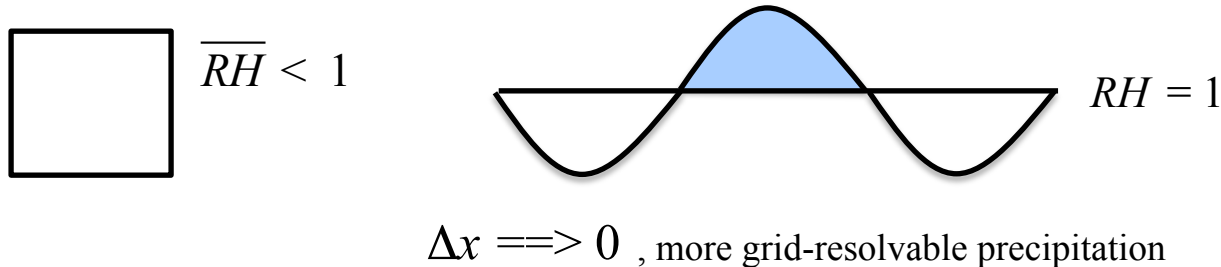
Concept : precipitation algorithms (CPS and MPS)

- In real atmosphere, dynamical motion $\rightarrow RH > 1 \Rightarrow$ clouds form $\rightarrow$ produces rain

- In modeled atmosphere, $RH < 1$

But generate clouds by releasing CAPE $\rightarrow$ requires parameterized process

Deep convection : 1~10km



Thus, we need the cumulus parameterization scheme to account for releasing conditional instability due to subgrid scale motion

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

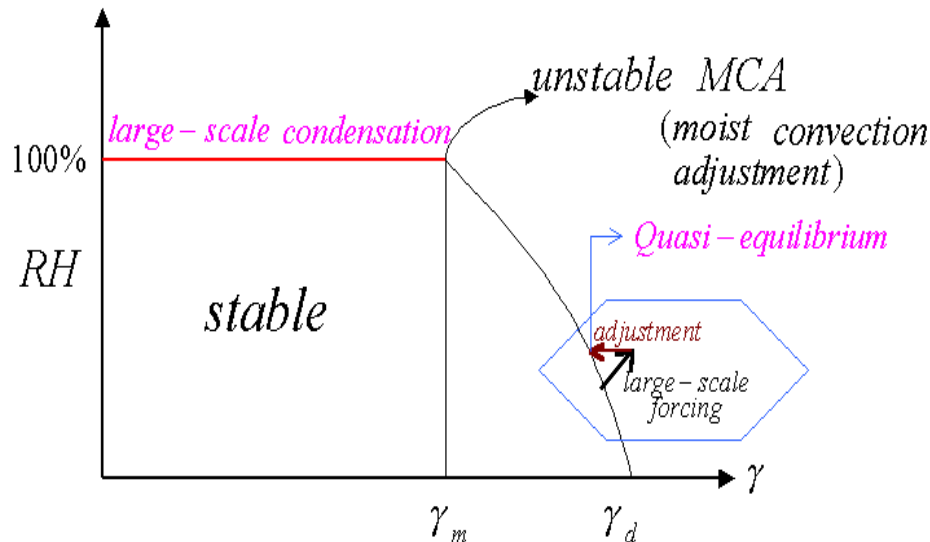
5. Cumulus parameterization scheme

Parameterized convection
Deep convection
Subgrid-scale precipitation
Implicit precipitation

5.1 Concept

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

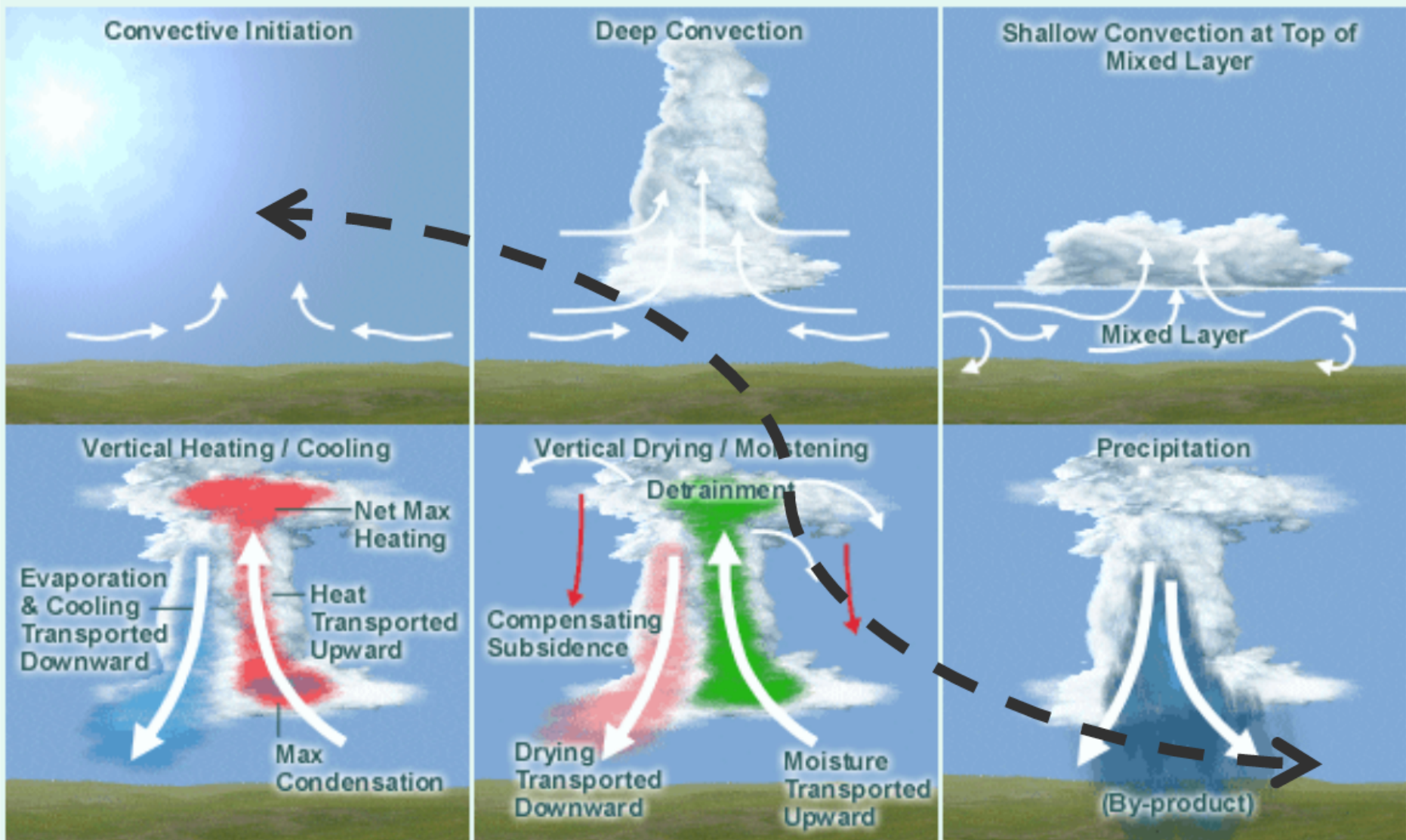
● Closure assumption



Jul 25, 2010, Seoul

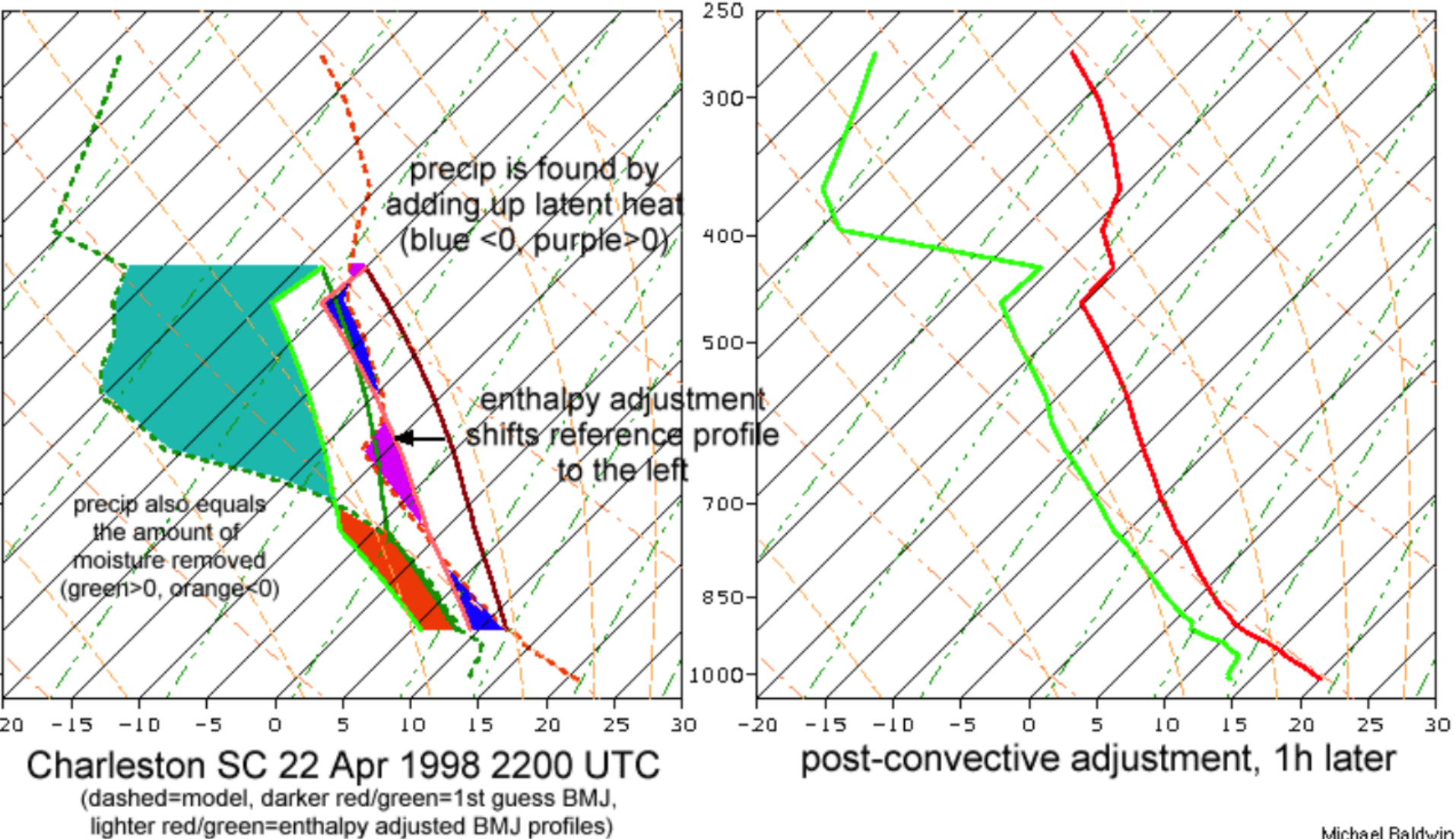
b

Processes CP Schemes Need to Account For



The COMET Program

CPS does not consider the detailed evolution of convection !



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 et 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

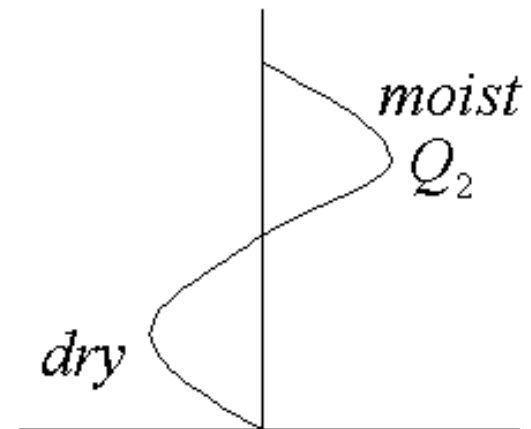
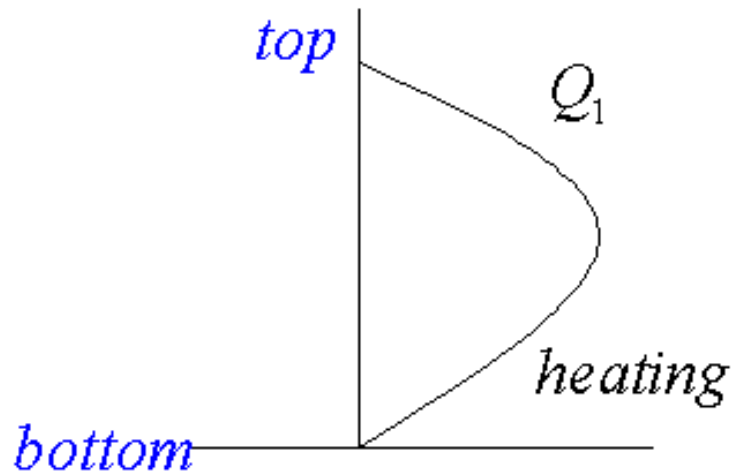
$$b = \left(\frac{1 - RH}{1 - RH_c} \right)^n$$

- Heating and moistening profiles

$$\frac{d\theta}{dt} = \frac{1}{\pi} [gL(1-b)M_t Q_1 + Q_r]$$

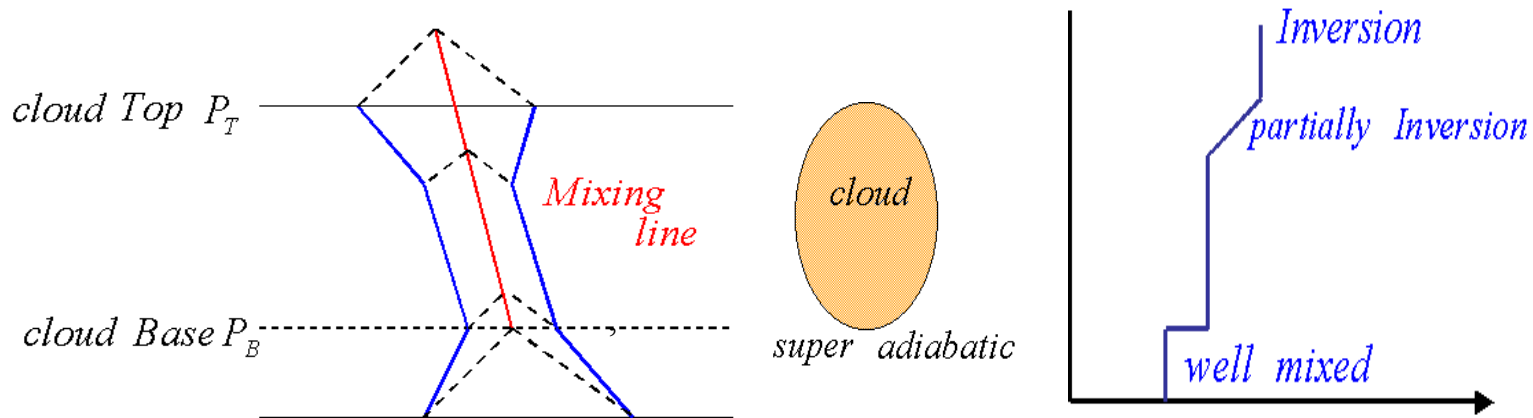
$$\frac{dq}{dt} = -g(1-b)M_t Q_2$$

$$\int_0^{P_s} Q_1 dp = \int_0^{P_s} Q_2 dp = 1$$



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

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

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

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

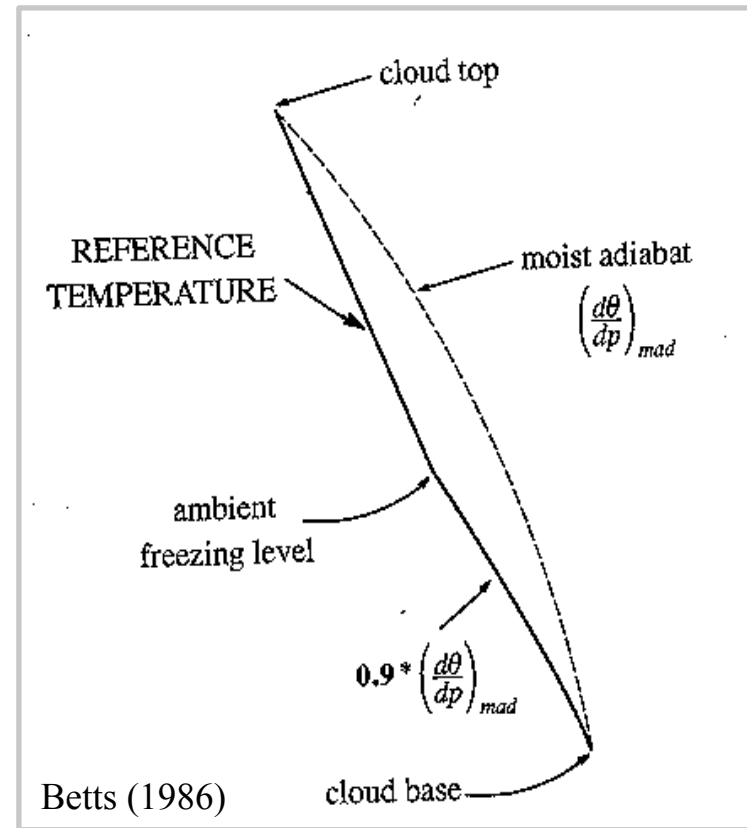
$$\text{Energy Constraints : } \int_{P_B}^{P_{T+1}} C_P (T_R - \bar{T}) dp = \int_{P_B}^{P_{T+1}} (q_R - \bar{q}) dp = 0$$

- Convective tendencies & Precipitation

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

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

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

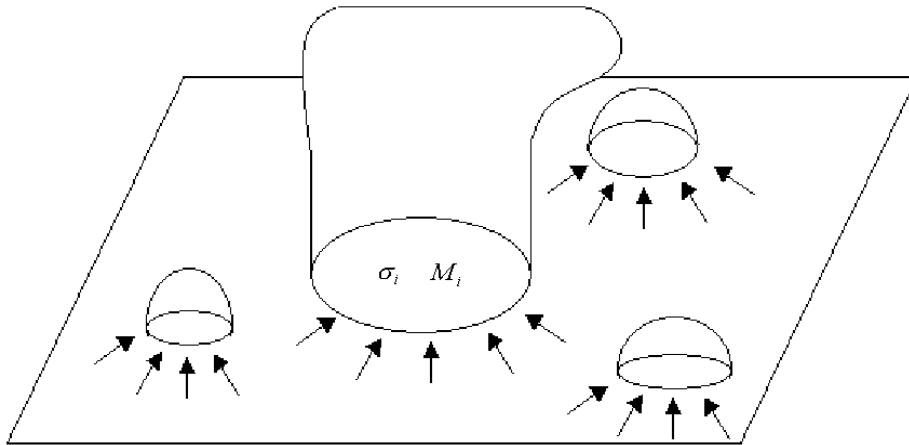


- **Remarks :**
 - Manabe (hard adjustment : toward a moist adiabat)
 - Kuo, BM (soft adjustment : toward reference profiles)

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

$\rho M = M_c + \tilde{M}_{\text{environment}}$
 : net mass flux/unit large-scale horizontal area

ii) Quasi-equilibrium : cloud forcing $\sim$ large-scale adjustment

: CPS computes the warming (cooling) in the grid box due to adiabatic descent (ascent), rather than computing latent heat releaser in cloud models

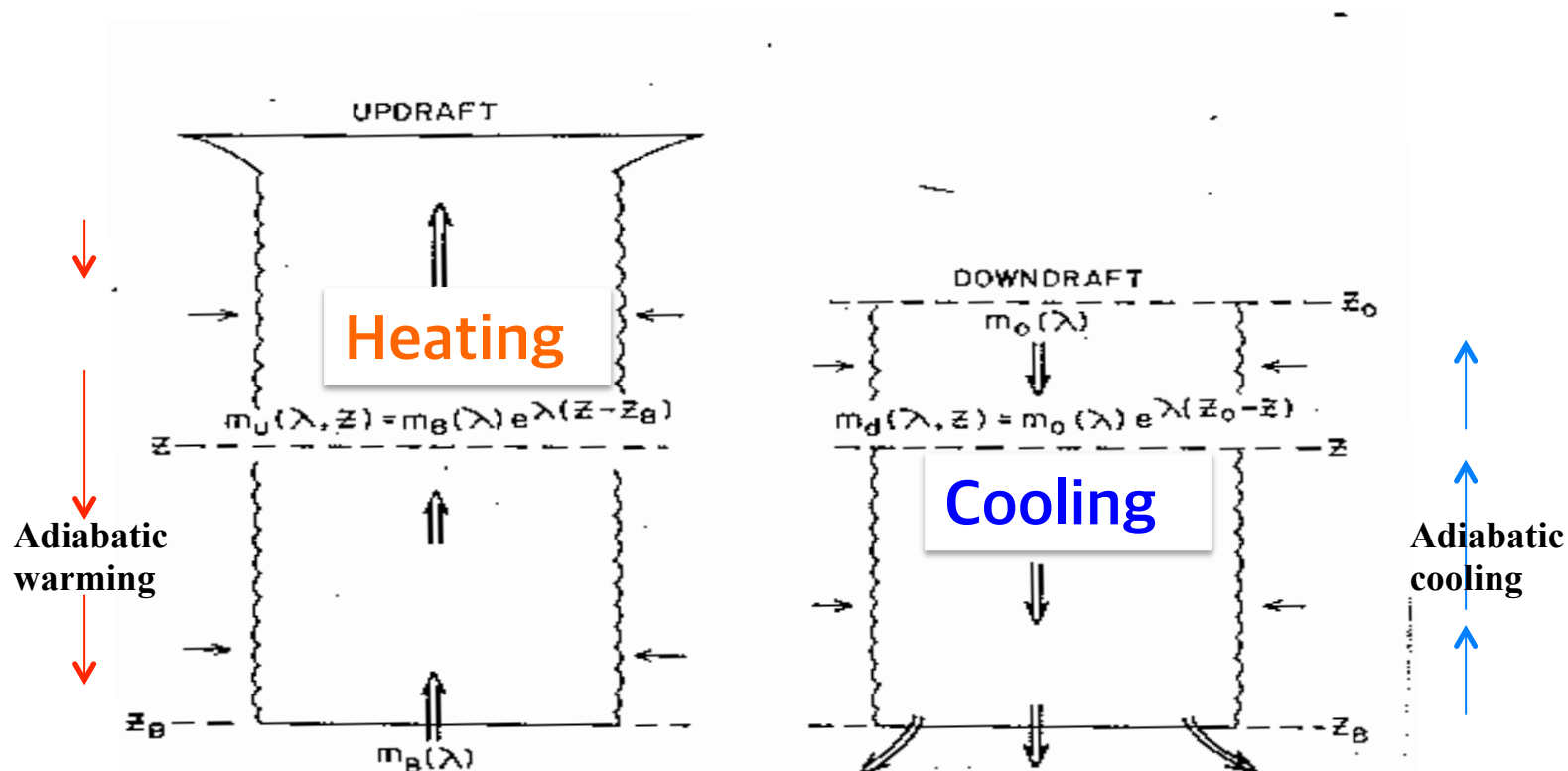


FIG. 4.10. Model for updraft and downdraft of cloud type λ (from Johnson 1976).

iii) Energy budget equations

Large-scale flux across grid box

Exchange of S between environment and clouds

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

$$\frac{\partial}{\partial t} \rho \sum \sigma_i S_i = -\frac{\partial}{\partial z} \left(\sum_i M_i S_i \right) + \sum_i \left(\frac{\partial M_i}{\partial z} + \rho \frac{\partial \sigma_i}{\partial t} \right) S_{ib} + \sum_x (LC_i + Q_{Ri})$$

S_i : $C_p T + gz$ (dry static energy) of i^{th} cloud

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

C_i : condensation in the i^{th} cloud

E : evaporation of liquid water in the environment

Q_r : Radiative heating

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

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

iv) Approximation

- Assume $\sigma_c \ll 1$, $\bar{s} \approx \tilde{s}$

$$\begin{aligned} \frac{\partial}{\partial t} \rho \bar{s} = & -\nabla \cdot (\rho \bar{v} \bar{s}) - \frac{\partial}{\partial z} (\rho \bar{w} \bar{s}) - \overline{\nabla \cdot (\rho \bar{v} s - \rho \bar{v} \bar{s})} \\ & + M_c \frac{\partial \bar{s}}{\partial z} - \sum_{dc} \left(\frac{\partial M_i}{\partial z} + \rho \frac{\partial \sigma_i}{\partial t} \right) (\delta_i - \bar{s}) - LE + \theta_R \end{aligned}$$

Detraining clouds
detrainment, entrainment

Adiabatic warming due to hypothetical subsidence between the clouds

$$\begin{aligned} \frac{\partial}{\partial t} \rho \bar{q} = & -\nabla \cdot (\rho \bar{v} \bar{q}) - \frac{\partial}{\partial z} (\rho \bar{w} \bar{q}) - \overline{\nabla \cdot (\rho \bar{v} q - \rho \bar{v} \bar{q})} \\ & + M_c \frac{\partial \bar{q}}{\partial z} - \sum_{dc} \left(\frac{\partial M_i}{\partial z} + \rho \frac{\partial \sigma_i}{\partial t} \right) (q_i - \bar{q}) - E \end{aligned}$$

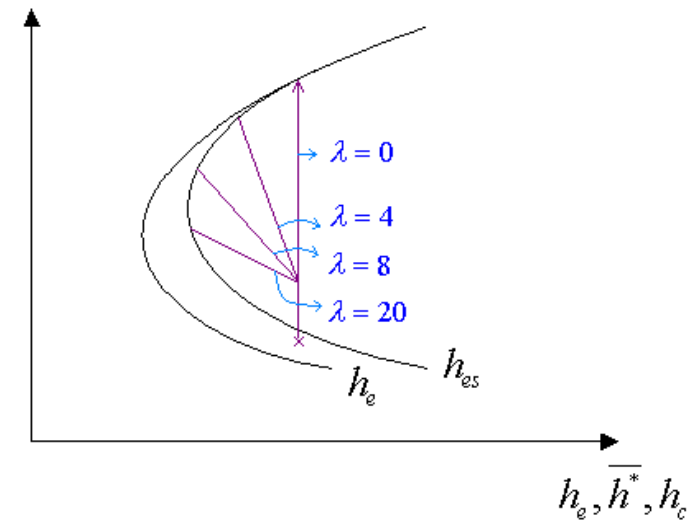
- Spectral cloud ensemble :

$$\begin{aligned} M_c(z) &= \int_0^{\lambda_{\max}} m(z, \lambda) d\lambda \quad \text{Sub-ensemble} \\ & \quad \text{mass flux of between } \lambda \text{ and } d\lambda + \lambda \\ &= \int_0^{\lambda_{\max}} m_B(\lambda) \eta(z, \lambda) d\lambda \\ \eta(z, \lambda) &\equiv \frac{m(z, \lambda)}{m_B(\lambda)} \quad \text{Mass flux at cloud base} ; \text{ normalized subensemble mass flux} \end{aligned}$$

v) Closure

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

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



- Cloud work function

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

- Q-G equilibrium

$$\frac{dA(\lambda)}{dt} = \underbrace{\frac{dA(\lambda)}{dt} \Big|_{LS}}_{\text{Large-scale forcing}} + \underbrace{\frac{dA(\lambda)}{dt} \Big|_C}_{\text{Adjustment}} ; 0$$

Large-scale forcing
>0 : destabilized

Adjustment
<0 : stabilization

Kernel : Cloud scheme kinetic energy

$$K_{ij} = \frac{A'_i - A_i}{(m_B \Delta t)} \quad \sum_j^{i_{\max}} K_{ij} (m_B \Delta t)_j + F_i = 0 \Rightarrow m_B$$

→ compute $\frac{\partial \bar{s}}{\partial t}, \frac{\partial \bar{q}}{\partial t}$ with η, m_B

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

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

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

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

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

6.3 Impact of the shallow convection scheme

JJA 1996 simulation in a GCM

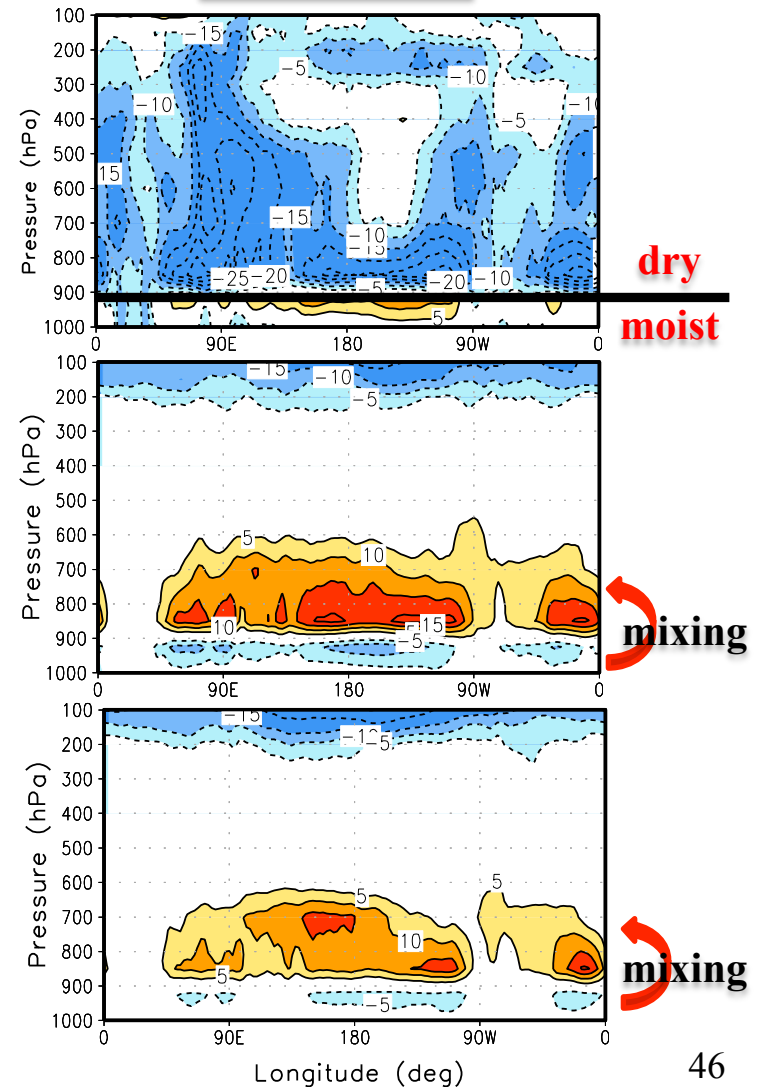
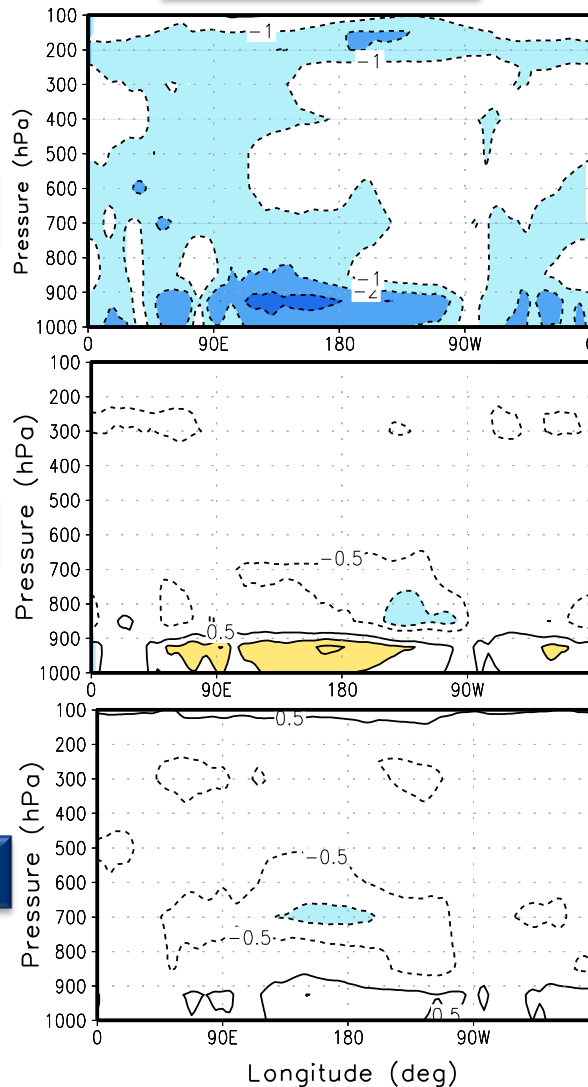
NO – RA2

Tiedtke – NO

Han and Pan–NO

Temperature

RH



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.

The slope parameter of the size distributions for rain λ_R is determined by multiplying (A1) by drop mass (A4) and integrating over all diameters and equating the resulting quantities to the appropriate water contents ($= \rho q_R$). This may be written as,

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

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

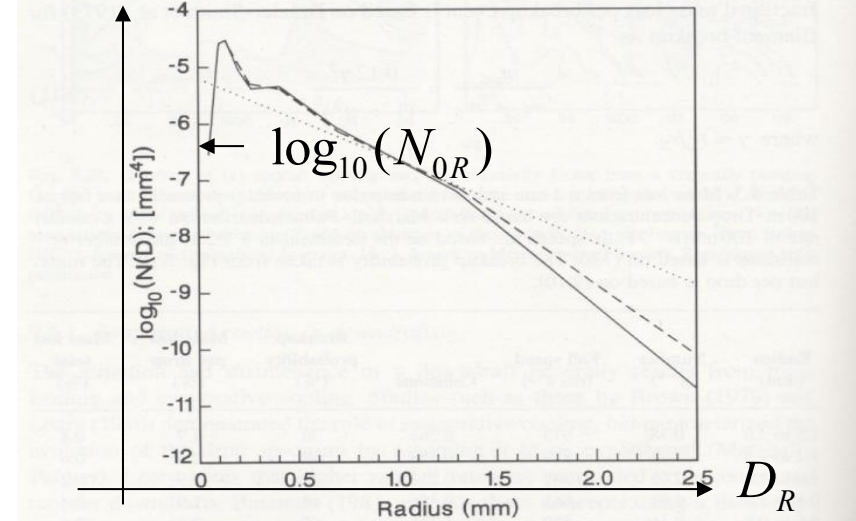


FIG. 9.21. Evolution of a drop spectrum in a subsaturated rainshaft including the effects of coalescence and breakup. The spectrum at the top of the rainshaft is Marshall–Palmer with a rainfall rate of 110 mm h^{-1} . (.....), 0 km; (---), 1 km; (—), 2 km; $R = 110 \text{ mm h}^{-1}$; $t = 24 \text{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

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

$$\begin{aligned} & \int_0^{\infty} D_R^{4-1} \exp(-\lambda_R D_R) dD_R \\ &= \Gamma(4) / \lambda_R^4 \end{aligned}$$

7.4 Bulk Method : 1-Moment versus 2-Moment

Mixing Ratio

(1-moment/ 2-moment scheme)

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

Number concentration

(2-moment scheme)

$$\left(\int \frac{d \text{Prob}(D_R)}{dt} dN_{DR} \right) = \frac{dN}{dt} (m^{-3} s^{-1})$$



Single moment scheme

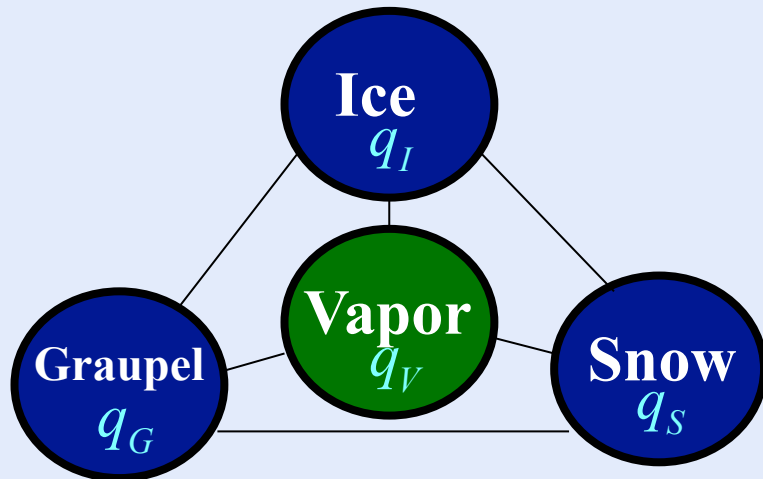
$$dN_{DR} = N_{0R} \exp(-\lambda_R D_R) dD_R$$

Double moment scheme

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

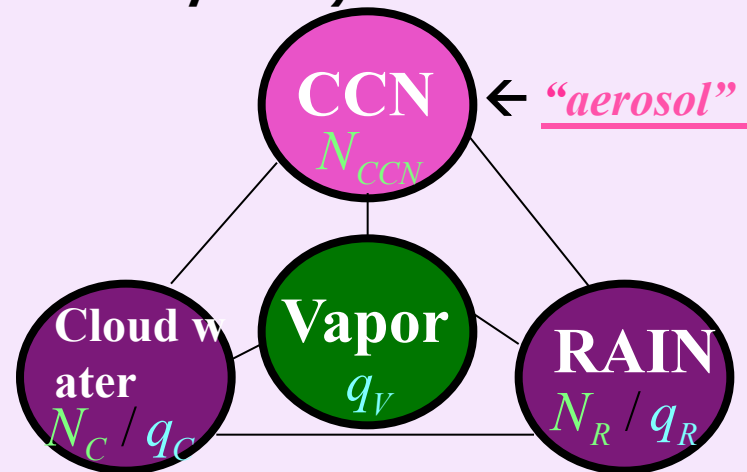
7.5 Bulk Method : 1-Moment (WSM) versus 2-Moment (WDM)

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



q for 4 hydrometeors will be predicted (Single Moment)

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



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 (Hong and Lim 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/dtclld

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)/dtclld)

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)/dtclld)
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)/dtclld)
    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)/dtclld)
  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)/dtclld)
    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)/dtclld)
  endif
endif
  
```

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

$$\text{Praut} [\text{kgkg}^{-1}\text{s}^{-1}] = L / \tau \quad L = 2.7 \times 10^{-2} \rho_a q_c \left(\frac{10^{20}}{16 \lambda_c^4} - 0.4 \right)$$

$$\tau = 3.7 \frac{1}{\rho_a q_c} \left(\frac{0.5 \times 10^6}{\lambda_c} - 7.5 \right)^{-1}$$

$$\text{Nraut} [\text{m}^{-3}\text{s}^{-1}] = 3.5 \times 10^9 \frac{\rho_a L}{\tau}$$

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

$$D_R \geq 100 \mu\text{m}$$

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

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

$$D_R < 100 \mu\text{m}$$

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

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

Resolution Dependency

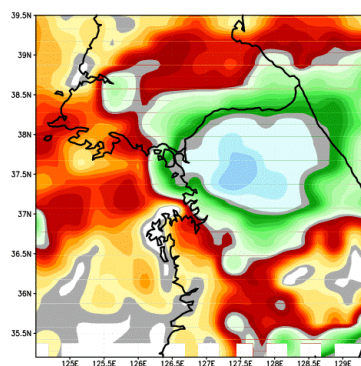
Cut-off horizontal grid length: current status in research communities

- 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)

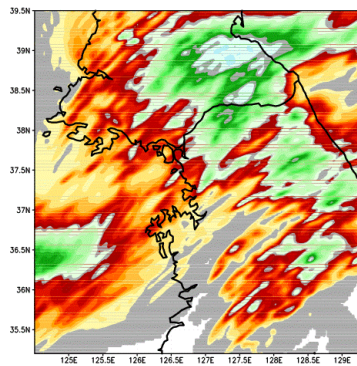
Gray-zone : partly resolved and partly parameterized

- 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

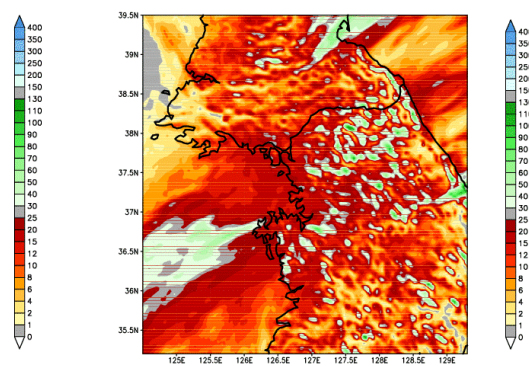
CPS gray-zone issue : A heavy rainfall simulated by WRF at 3 km



OBS



No CPS



With CPS

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Thanks for your attention !

Modeling is to understand what is
happening in nature !