Overview of Physical Parameterizations

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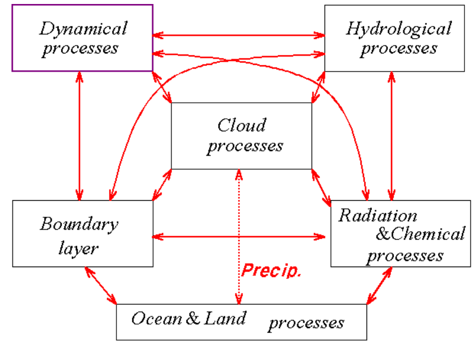
1) Concept



*** 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**

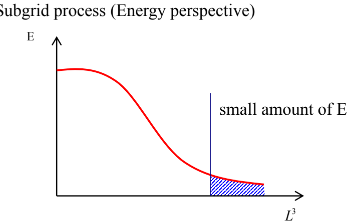
The formulation of physical process in terms of the model variables as parameters, i.e., constants or functional relations.

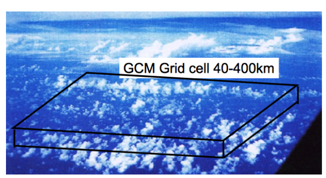
1) Concept…continued

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

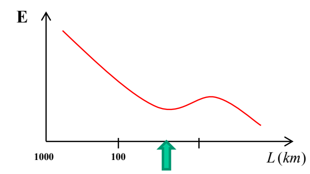
Objective of subgrid-scale parameterization

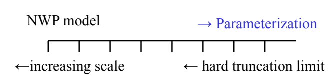
"To design the physical formulation of energy sink, withdrawing the equivalent amount of energy comparable to cascading energy down at the grid scale in an ideal situation."

1) Concept…continued

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

Model

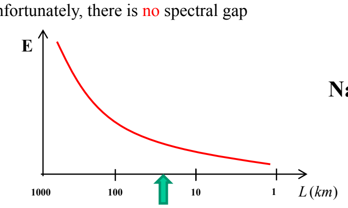




where truncation limit ; spectral gap

Unfortunately, there is no spectral gap

Nature



2) Subgrid scale process & Reynolds averaging

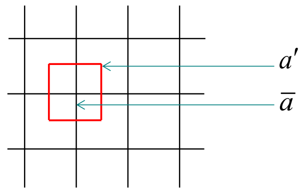
Consider prognostic water vapor equation

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

In the real atmosphere,

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

ρ' is neglected



2) Subgrid scale process & Reynolds averaging…continued

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

then eq.(1) becomes

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

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

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

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

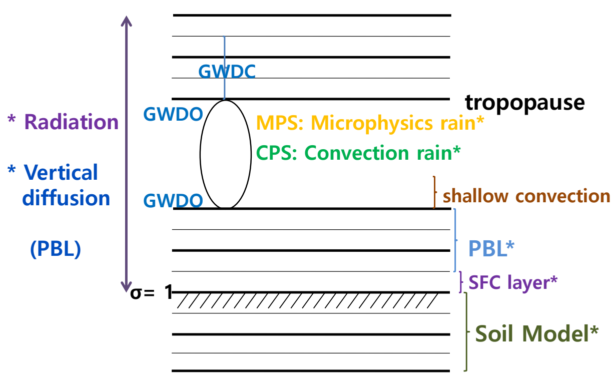
taking Reynolds averaging,

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

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

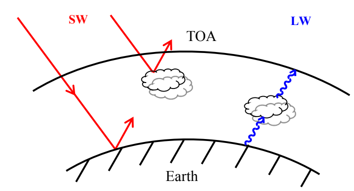
3) Schematic of physics algorithm : In modeled atmosphere : 7* (essential) ~10

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



1. Radiation

1.1 Concept



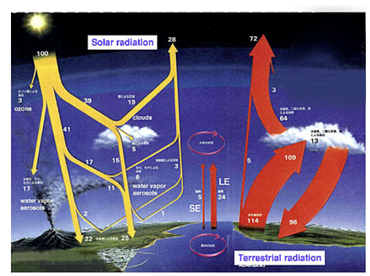
TOA (top of the atmos) : S = 1360 Wm^{-2}

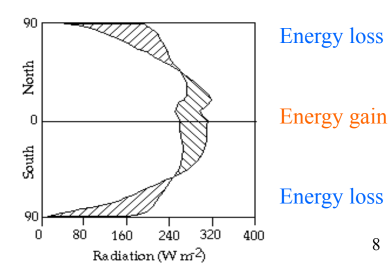
Mean Flux : $\frac{S}{4} = 340\ Wm^{-2}$ → Energy source for Earth

30% : reflected from the atmosphere clouds

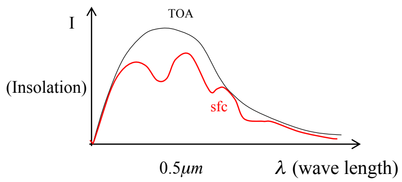
→ Back to space by terrestrial infrared radiation

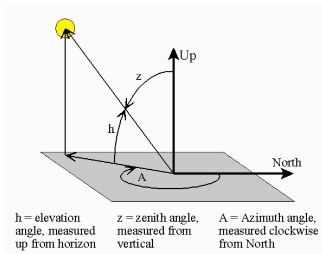
25% : absorbed in the atmosphere
45% : absorbed at the earth surface





1.2 Solar radiative transfer





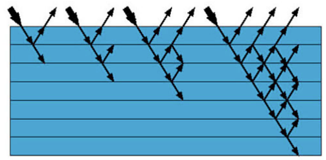
- At TOA,

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

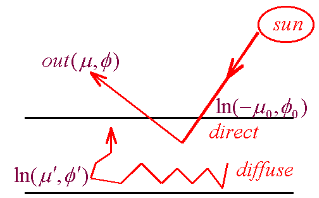
- Basic equations $\mu = \cos\theta$

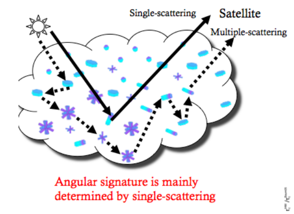
$$\mu \frac{dI(\tau,\mu,\phi)}{d\tau} = I(\tau,\mu,\phi) - J(\tau,\mu,\phi)$$

absorption source emission



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





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

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

P : Scattering phase function :redirects (μ',ϕ') (μ,ϕ)

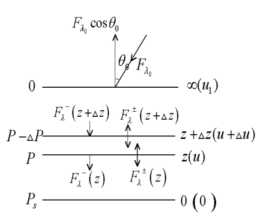
$\tilde{\omega} = \frac{\sigma_s}{\sigma_e}$: Scatteing albedo

scattering cross section/extinction(scattering + absorption) cross section

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

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

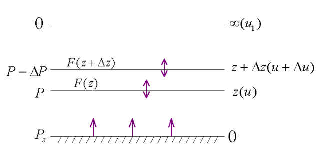
$$P(\cos\phi) = \sum_{l=0}^{N} \tilde{\omega}_l P_l(\cos\phi) \qquad \text{: Legendre Polynomial}$$



Radiative transfer equation solver.

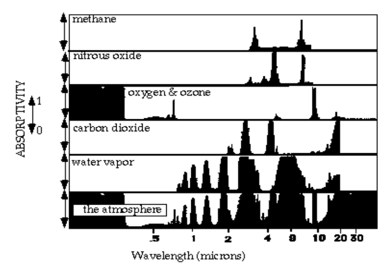
→ Discrete - ordinates method
Two - Stream and Eddington's approximation
Delta - function adjustment and similarity principle
δ - Four stream approximation

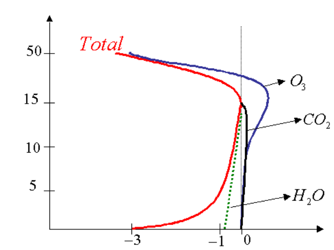
1.3 Terrestrial radiation



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

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



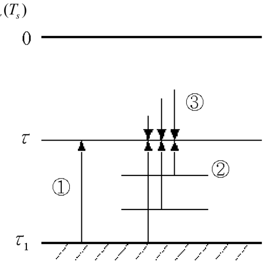


In spectral bands (monochromatic)

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

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

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



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

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

$$d\tau = -k_\nu \rho dz \quad \tau_1 = \int_0^{u_1} k_\nu du, \qquad u_1 = \int_0^\infty \rho dz \text{ (path length)}$$

LW is time consuming !

1.4 Cloud fraction

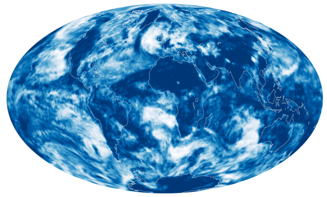
i) Ealier method (Slingo)

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

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

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

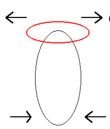
where RH_0 is the critical value of RH, which is optimized based on observations



ii) Advanced method (Chou)

- inclusion of ice, liquid 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)



→ detrained

$u_{q_c}, u_{q_i}, k_{q_c}, k_{q_i}$ in radiation code

f_l use the hydrometeor information from microphysics routine (MPS), $q_c, q_s, q_i, \cdots$

iii) Radiation properties

$\tau_i^c = cwp[a_i + \frac{b_i}{r_{ei}}] f_{ice}$ (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-

$\overline{\tau_c} = \sum_i \tau_i$ i : 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

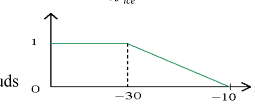
$h_l = a \ln(1.0 + \frac{b}{g}\int_{P_t}^{P_s} q dp)$

- cloud droplet size,

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

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

- ice fraction, f_{ice}



- For prognostic microphysics scheme,

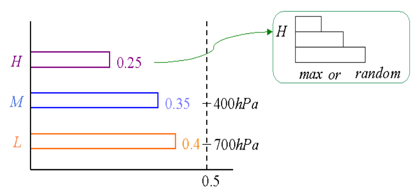
: Broadband radiation : Radiative properties are explicitly computed from prognostic water substances

: Simplified radiation : Dudhia (1989)

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

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

iv) Cloud overlapping



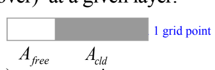
Maximum overlapping : 0.4

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 $A_c, (1-A_c)$ → summation

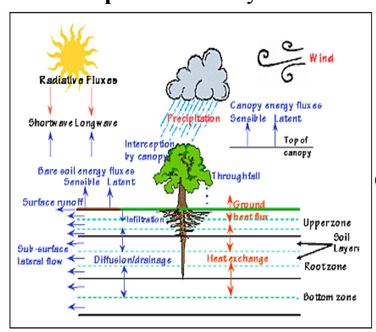
- Issues : $A_c = 0$ or 1 ← in WRF versus partial cloudiness in GFS : WRF has partial cloudiness recently

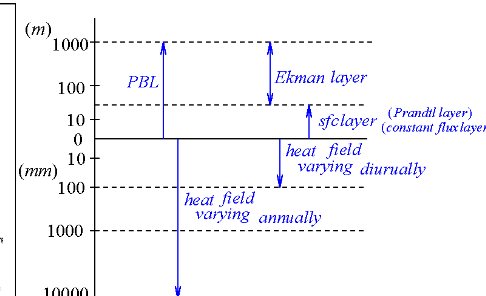
- Interaction : Radiation

Cloud

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)

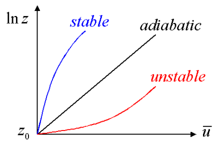
$$H_0 = \rho C_p C_H |\vec{V}_a| \Delta T$$
$$E_0 = \rho L C_H |\vec{V}_a| \Delta q M_a$$
$$\vec{\tau}_0 = \rho C_D |V_a| \vec{V}_a$$

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



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

Φ : curving factor

※ **Profile function** : ϕ_m and ϕ_t

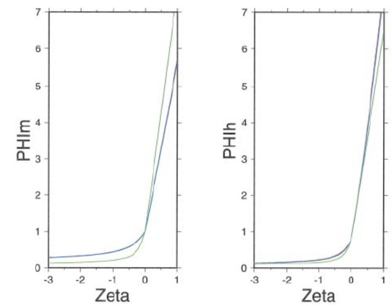
Dyer and Hicks formula for similarity

- 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)

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



Kantha (2003)

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

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

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

※ **Useful relation** :

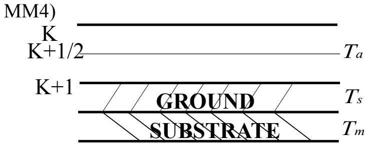
Given the F_m, F_H $C_D = k^2/F_m^2, C_Q = C_H = k^2/(F_m F_t)$ $u_* = kU/F_m$

$$\tau_0 = \rho k_m \frac{du}{dz} = -\overline{u'w'} = \rho C_d U^2$$
$$H_0 = -\rho C_p k_h \frac{d\theta}{dz} = \rho C_p \overline{\theta' w'} = -\rho C_p C_H U \Delta\theta$$
$$E_0 = -\rho L \overline{q'w'} = -\rho L C_q U \Delta q$$

2.3 Soil model

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

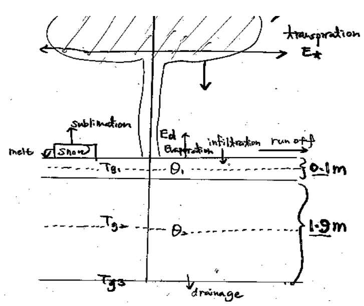
$$\frac{\partial T_s}{\partial t} = \lambda_T(R_n - LE - H) - \frac{2\pi}{\tau}(T_s - T_a)$$
$$\frac{\partial T_s}{\partial t} = \frac{1}{\tau}(T_s - T_m) \quad : T_m\text{, daily mean}$$



2) Multi-layer model : OSU method

$$\frac{\partial T_s}{\partial t} = \lambda_T(R_n - LE - H) \quad \text{: surface T}$$
$$(\rho C)_i \frac{\partial T_g}{\partial t} = \frac{\partial}{\partial z}(\lambda T_g \frac{\partial T_g}{\partial z}) \quad \text{: soil T}$$
$$\frac{\partial\Theta}{\partial t} = \frac{\partial}{\partial z}(D\frac{\partial\Theta}{\partial z}) + K\frac{\partial\Theta}{\partial z} + F_\Theta \quad \text{: soil moisture}$$

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

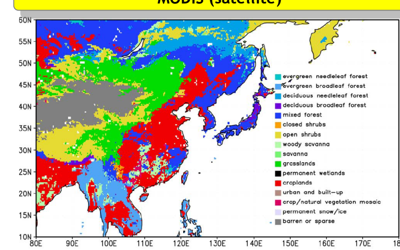


RA analysis: 2-layer soil mode l

2.4 Vegetation type → z_0, Albedo

Vegetation types

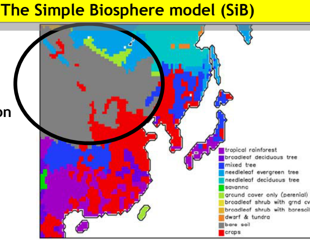
MODIS (satellite)



13 type data set
1 degree

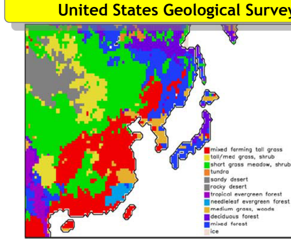
12 type data set
20 min

The Simple Biosphere model (SiB)



quite broad desert region

United States Geological Survey's (USGS)

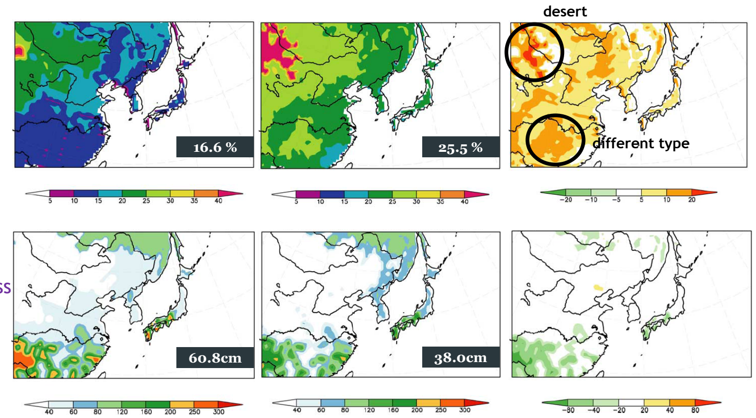


Albedo and roughness length (z_0)

Sib | USGS | USGS-Sib

Albedo

Roughness length

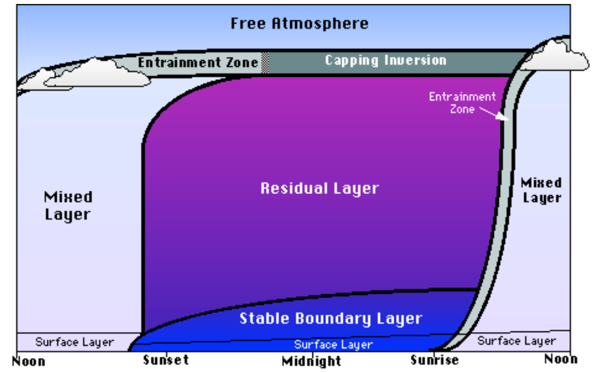


Much uncertainties in calibration/optimization !!!

3. Vertical diffusion (PBL)

3.1 Concept

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



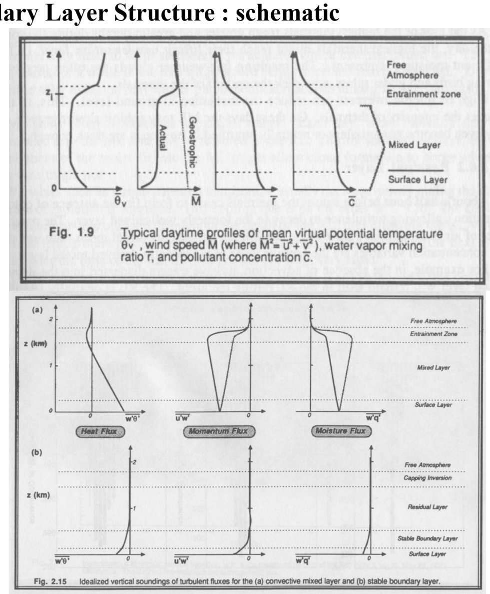
Structure of Planetary Boundary Layer
adapted from Stull, 1988.

3.2 Planetary Boundary Layer Structure : schematic

Daytime profiles

Daytime flux profiles

Nighttime flux profiles



Stull (1988)

3.3 Classifications : how to determine, k_c

i) Local diffusion (Louis 1979)

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

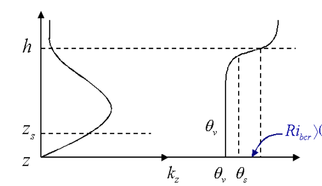
Local Richardson number

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 et al. 2007)

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

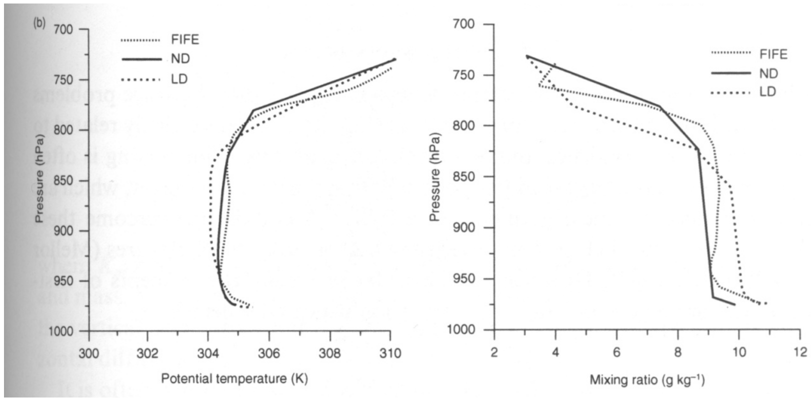
small eddies strong updrafts

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 = 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 nearneutral or slightly stable BL in the upper part of BL

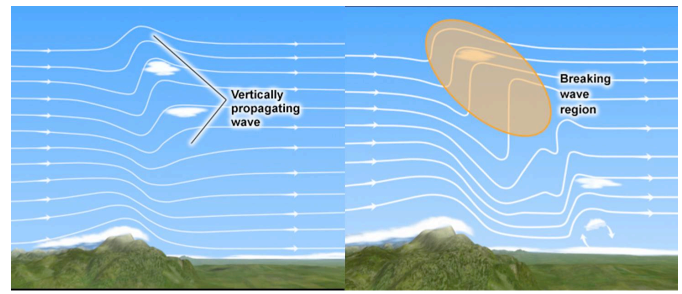
Hong and Pan (1996)

4. Gravity Wave Drag

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

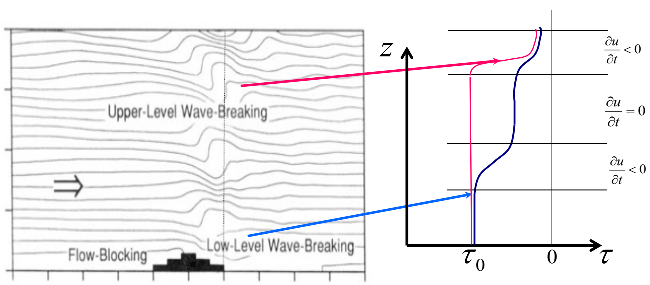
4.1 Concept

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.



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

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



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

$$\frac{\partial v}{\partial t} = -\frac{1}{\rho}\frac{\partial \tau_y}{\partial z}$$

Stress at reference level : $\tau_0 = -E\frac{1}{\Delta x}\frac{\rho_0 U_0^3}{N_0}\frac{Fr^2}{Fr^2+0.5/OC},\ U_0 = \frac{1}{h}\int_{k=1}^{k=kpbl} U dz$

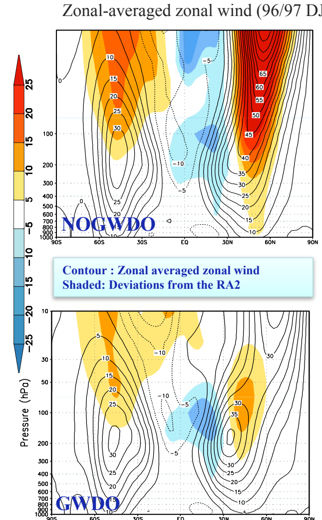
Reference level (KA95) : Max (2, KPBL)

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

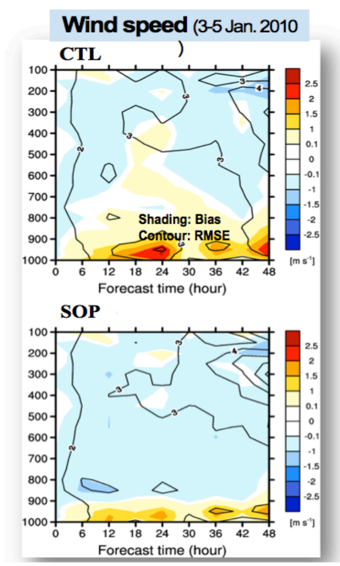
Advanced: the higher-moment orographic statistics-based wave- breaking mechanism using half-theory (Scorer parameter ~ BVF**2 / U**2) and half-empiricism obtained from mesoscale mountain wave simulations, which breaks in the lower atmosphere as well as upper layer, together with flow blocking

4.3 Impact of GWDO

Zonal-averaged zonal wind (96/97 DJF)



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

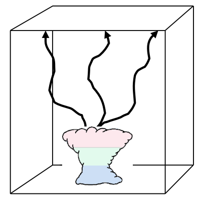


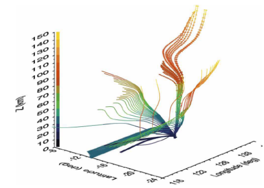
Flow blocking ➔ Improves the low-level winds (Choi and Hong, 2015)

4.4 Convective GWD (CGWD) or non-orographic GWD

CGWD parameterizations

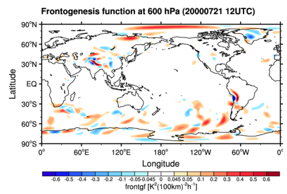
- Chun and Baik (1998, 2002): The momentum flux spectrum for the CGWD parameterization was **first analytically formulated**
- Song and Chun (2005): **Nonstationary parts** of convective GWs were included in the parameterization
- Song and Chun (2008): **Ray-based parameterization** that can represent 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





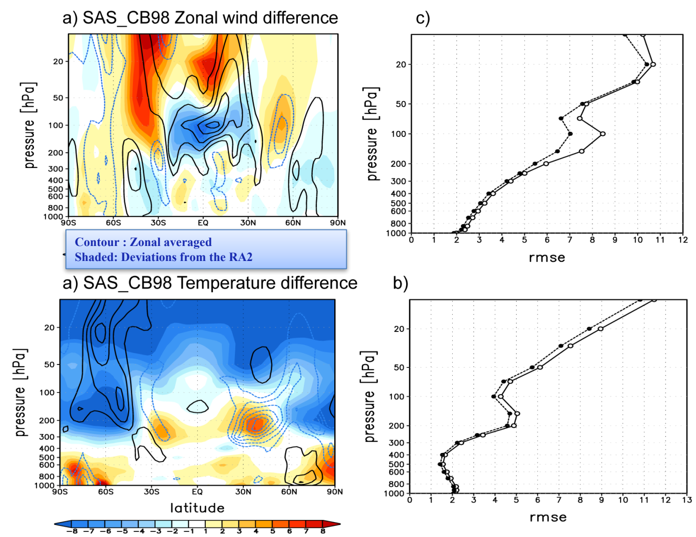
Jet/Front GWD parameterizations

- 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

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



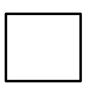
Wind and temperature RMSE are reduced in upper atmosphere

Precipitation Processes

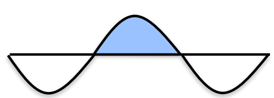
Concept : precipitation algorithms (CPS and MPS)

- In real atmosphere, dynamical motion -> 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



$\overline{RH} < 1$



$RH = 1$

Δx ==> 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

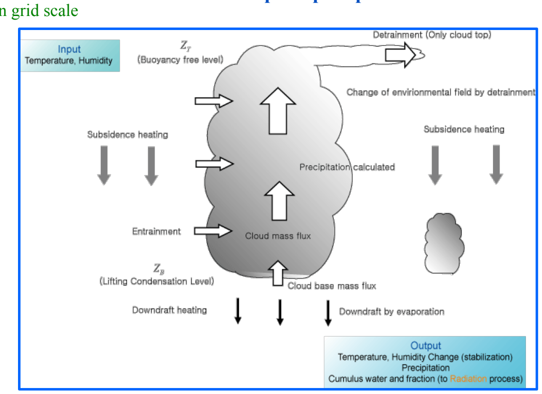
5. Cumulus parameterization scheme

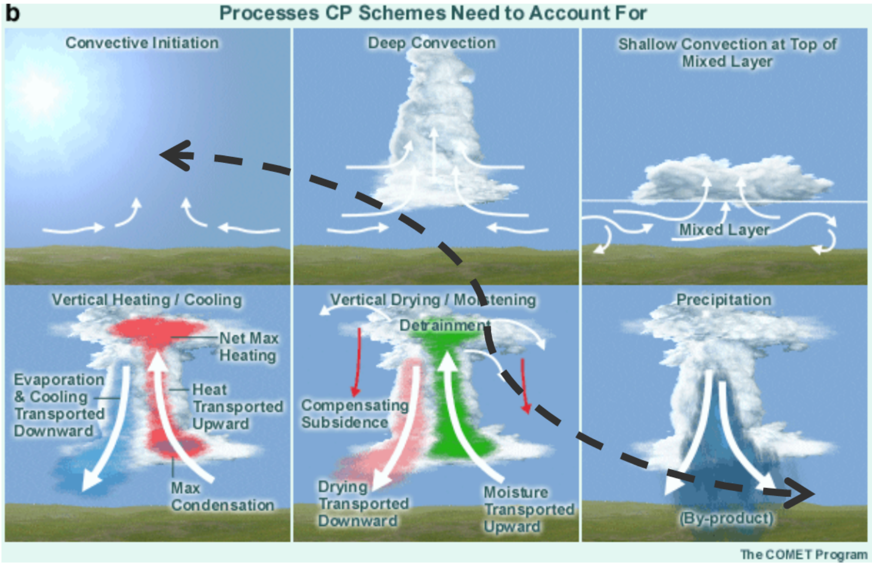
5.1 Concept

- 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

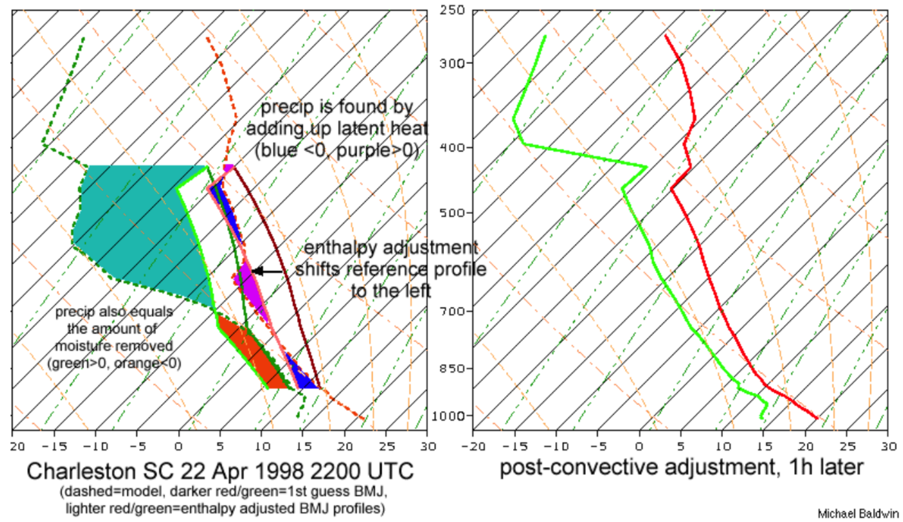
Parameterized convection
Deep convection
Subgridscale precipitation
Implicit precipitation

Jul 25, 2010, Seoul





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

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

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

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

- Modified Kuo scheme

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

vertical advection of moisture

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

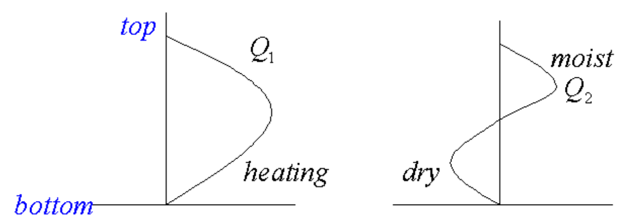
Anthes (AK : 1977) : a revised moistening factor and parcel buoyancy

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

- Heating and moistening profiles (prescribed)

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

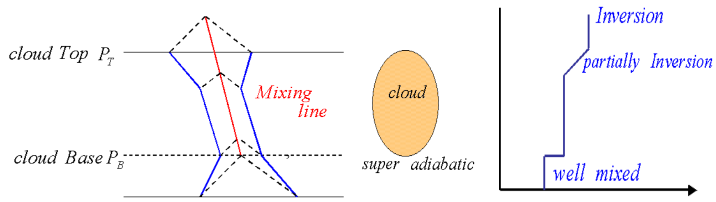
$$\frac{dq}{dt} = -g(1-b)M_tQ_2 \qquad \int_0^{P_s}Q_1dp = \int_0^{P_s}Q_2dp = 1$$



- 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

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

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

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

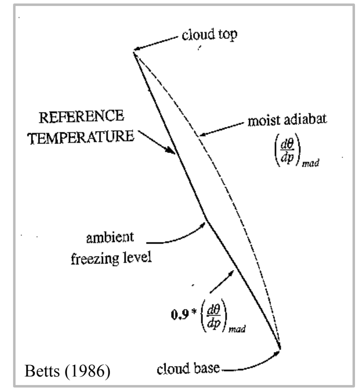
Energy Constraints : $\int_{P_B}^{P_{T+1}} C_P\left(T_R-\bar{T}\right)dp=\int_{P_B}^{P_{T+1}}\left(q_R-\bar{q}\right)dp=0$

- Convective tendencies & Precipitation

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

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

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



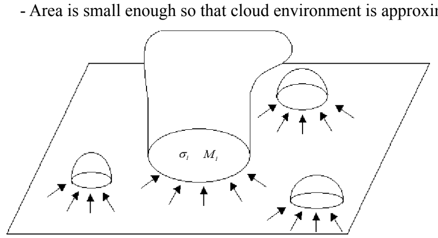
- Remarks : -Manabe (hard adjustment : toward a moist adiabat)
-Kuo, BM (soft adjustment : toward reference profiles

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

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

$\rho M = M_c+\tilde{M}$ (environment)

: 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

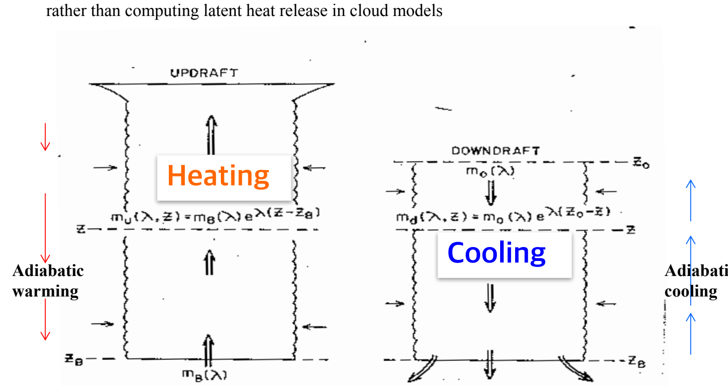


FIG. 4.10. Model for updraft and downdraft of cloud type λ (from Johnson 1976).

iii) Energy budget equations

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

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

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

$S_i : C_pT+gz$ (dry static energy) of i[th] cloud

$S_{ib} : C_pT+gz$ 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 $\sigma_c \ll 1\ ,\quad \bar{s}\simeq\tilde{s}$

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

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

Detraining clouds — detrainment, entrainment

Adiabatic warming due to hypothetical subsidence between the clouds

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

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

- Spectral cloud ensemble :

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

Sub-ensemble: mass flux of between λ and $d\lambda+\lambda$

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

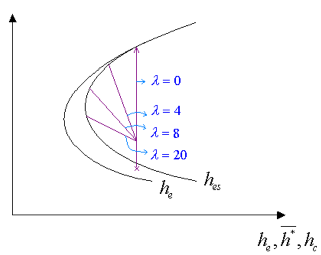
Mass flux at cloud base

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

v) Closure

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

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



- Cloud work function : measure of buoyancy

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

- 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 >0 : destabilized — Adjustment <0 : stabilization

Kernel : Cloud scheme kinetic energy

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

⟶ 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 (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)

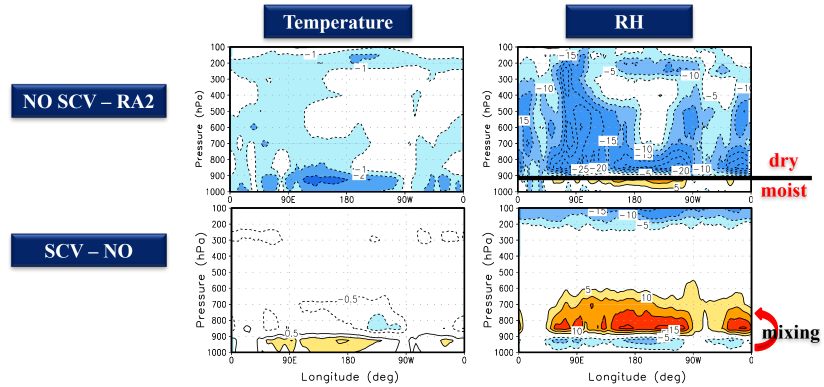
$$\frac{1}{\eta}\frac{\partial \eta}{\partial z} = \varepsilon - \delta$$

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

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

6.3 Impact of the shallow convection scheme (SCV)

: JJA 1996 simulation in a GCM



* 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

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

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.

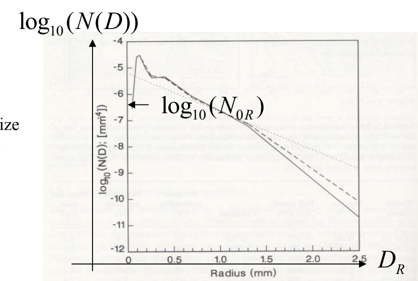


Fig. 9.21. Evolution of a drop spectrum in a subsaturated rainshaft including the effects of coalescence and breakup. The spectrum at the top of the rainshaft is Marshall–Palmer with a rainfall rate of 110 mm h^{-1}. (······), 0 km; (- - -), 1 km; (–), 2 km; R = 110 mm h^{-1}; t = 24 min. From Tzivion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

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

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

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

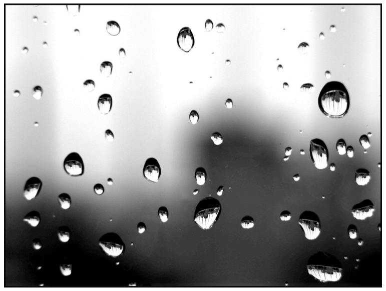
7.4 Bulk Method : 1-Moment versus 2-Moment

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

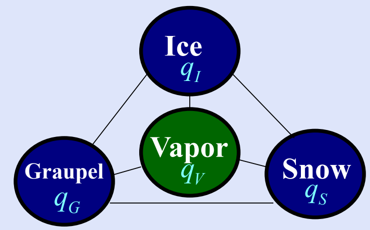
$$dN_{DR} = N_{0R} \exp(-\lambda_R D_R) dD_R$$

Double moment scheme

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

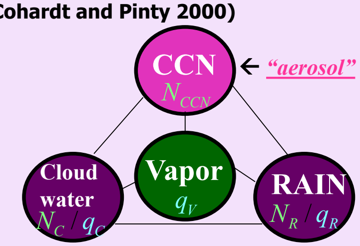
7.5 Bulk Method : 1-Moment (WSM) versus 2-Moment (WDM)

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** (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]**

$$\text{Praut [kgkg}^{-1}\text{s}^{-1}] = L/\tau \qquad L = 2.7\times10^{-2}\rho_a q_C\left(\frac{10^{20}}{16\lambda_C^4} - 0.4\right)$$

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

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

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

$D_R \geq 100$ μm

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

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

$D_R < 100$ μm

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

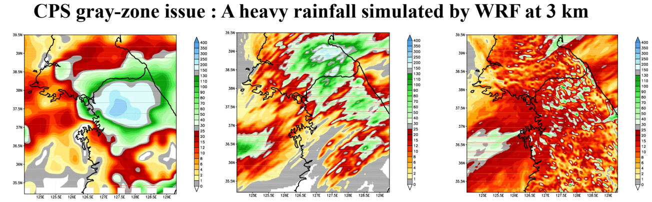
$$\text{Nracw[m}^{-3}\text{s}^{-1}] = -K_2 N_C N_R \left\{\frac{2}{\lambda_C^6} + \frac{5040}{\lambda_R^6}\right\}$$

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)

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



OBS **No CPS** **With CPS**

Gray-zone : partly resolved and partly parameterized (Hong and Dudhia 2012)

- 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

References

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

Arakawa, A., and C.-M. Wu, 2013: A unified representation of deep moist convection in numerical modeling of the atmosphere. Part 1. *J. Atmos. Sci.*, gttps://doi.org/10.1175/JAS-D-12-0330.

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.

Betts, A. K., and M. J. Miller, 1993: The Betts-Miller scheme. The representation of cumulus convection in numerical model pp107-121(book).

Boutle, I. A., R. J. Beare, S. E. Belcher, A. R. Brown, and R. S. Plant,2010: The moist boundary layer under a mid-latitude weather system. *Boundary-layer Meteor.,* 134:367-386, DOI 10.1007/s10546-009-9452-9.

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. *J. Atmos. Sci.*, 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.

Chou, C., and J. Dabid Neelin, 1999: Cirrus detrainment-temperature feedback. *Geophys. Res. Lett*., 26, 9, 1295-1295.

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

Grell, G. A. and Freitas, S. R., 2014: A scale and aerosol aware stochastic convective parameterization for weather and air quality modeling. *Atmos. Chem. Phys*., 14, 5233-5250.

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. R*ev., 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., and J. Dudhia, 2012: Next-Generation Numerical Weather Prediction: Bridging parameterization, explicit clouds, and large eddies. *Bull. Amer. Meteor. Soc*., 93(1), ES6–ES9, doi: 10.1175/2011BAMS3224.1.

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.

Honnert, R., V. Masson, and F. Couvreux, 2011: A diagnostic for evaluating the representation of turbulence in atmospheric models at the kilometric scale. *J. Atmos. Sci*., 68, doi: 10.1175/JAS-D-11-061.1

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.

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*., 145, 583-598.

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. *Mon. Wea. Rev*., DOI: 10.1175/MWR-D-14-00116.1

Siebesma, A. P., P. M. M. Soares, and J. Teixeira, 2007: A Combined Eddy-Diffusivity Mass-Flux Approach for the Convective Boundary Layer. J. Atmos. Sci., 64, 1230-1248.
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. *Bound.-Layer Meteor*, 37, 129-148.
Yamada, T., and G. Mellor, 1975: A simulation of the Wangara atmospheric boundary layer data. *J. Atmos.*

Thanks for your attention !

Modeling is to understand what is happening in nature !