How to develop the algorithm for physical processes in atmospheric models

Song-You Hong

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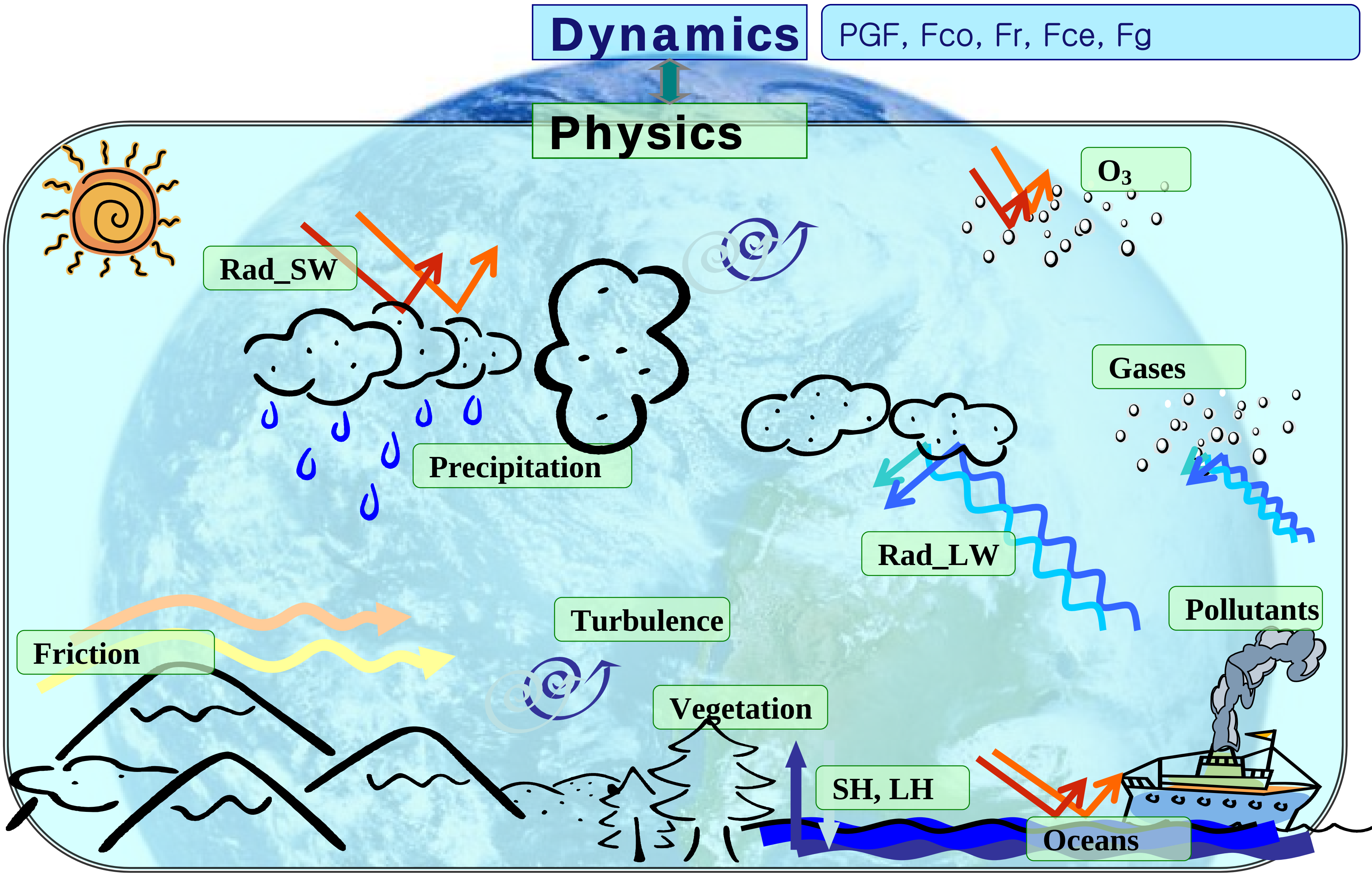
Presentation (NWP perspective)

- Introduction to the physics parameterizations
- Development strategy : Stable PBL processes
- Deterministic versus stochastic approach
- Strategy for development (personal)

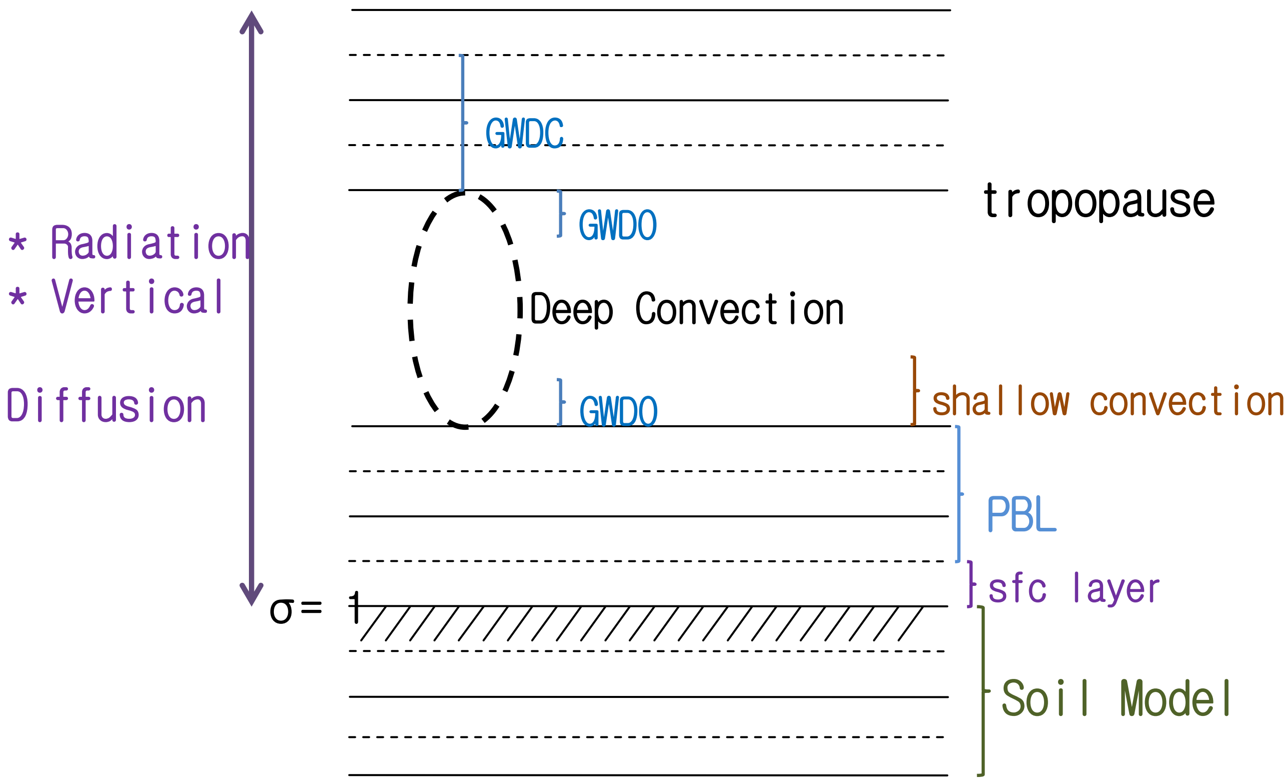
Numerical model



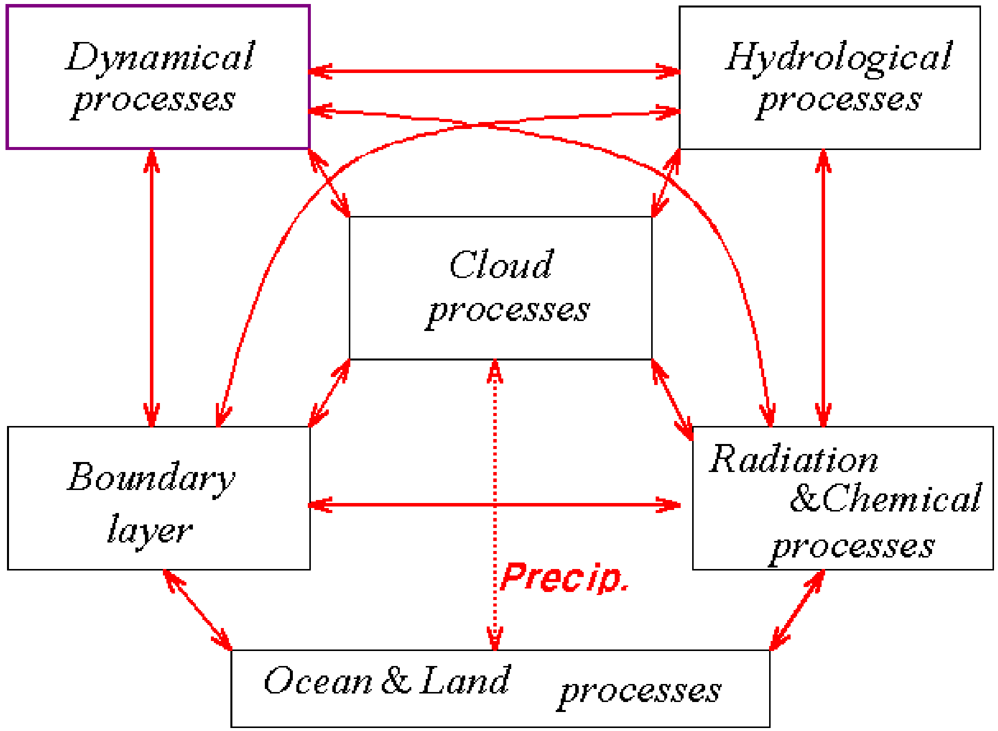
Introduction to Physical processes in atmosphere

concept

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



Introduction to Physical processes in atmosphere



* Physical process in the atmosphere

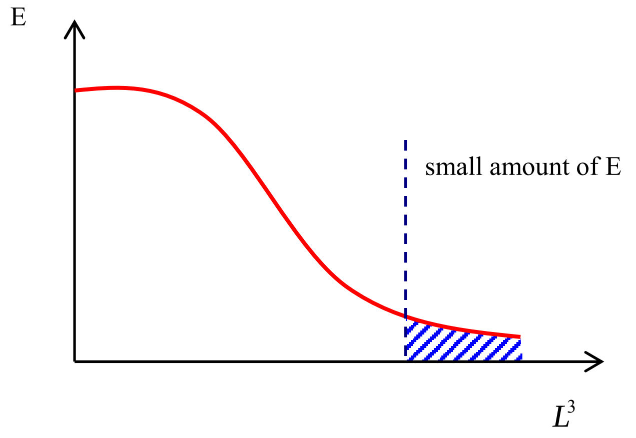
Specification of heating, moistening and frictional terms in terms of dependent variables of prediction model
→Each process is a specialized branch of atmospheric sciences.

Introduction to Physical processes in atmosphere

* Subgrid scale process (physics modeling)

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)



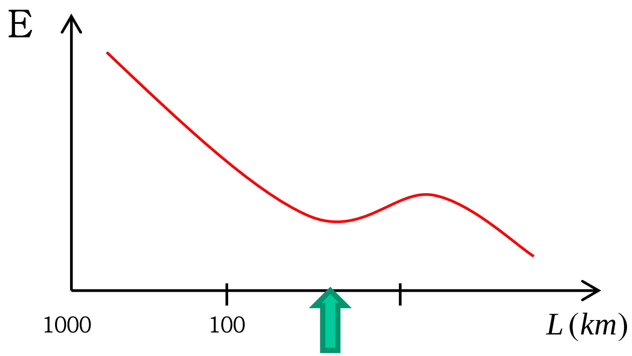
- $\Delta x \rightarrow 0$, the energy dissipation takes place by molecular viscosity (smallest grid size idealized situation)

- Objective of subgrid scale parameterization

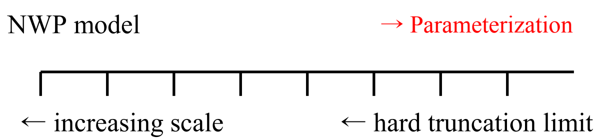
"To design the physical formulation of energy sink, withdrawing the equivalent amount of energy comparable to cascading energy down at the grid scale in an ideal situation."

Introduction to Physical processes in the atmosphere

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

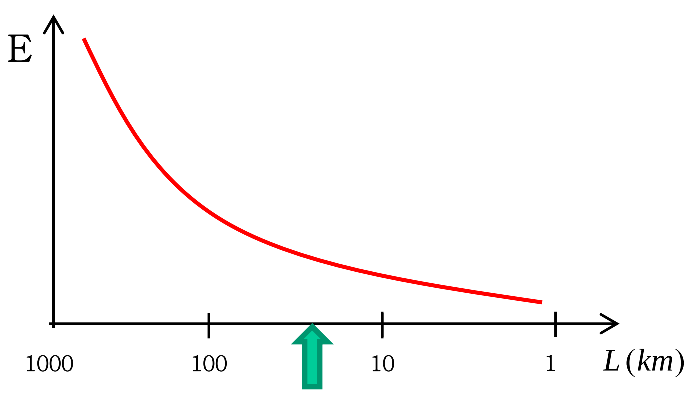


Model



Where truncation limit ; spectral gap

Unfortunately, there is no spectral gap



Nature

Development of physics algorithms

- Theoretical development (concept) : Step 1

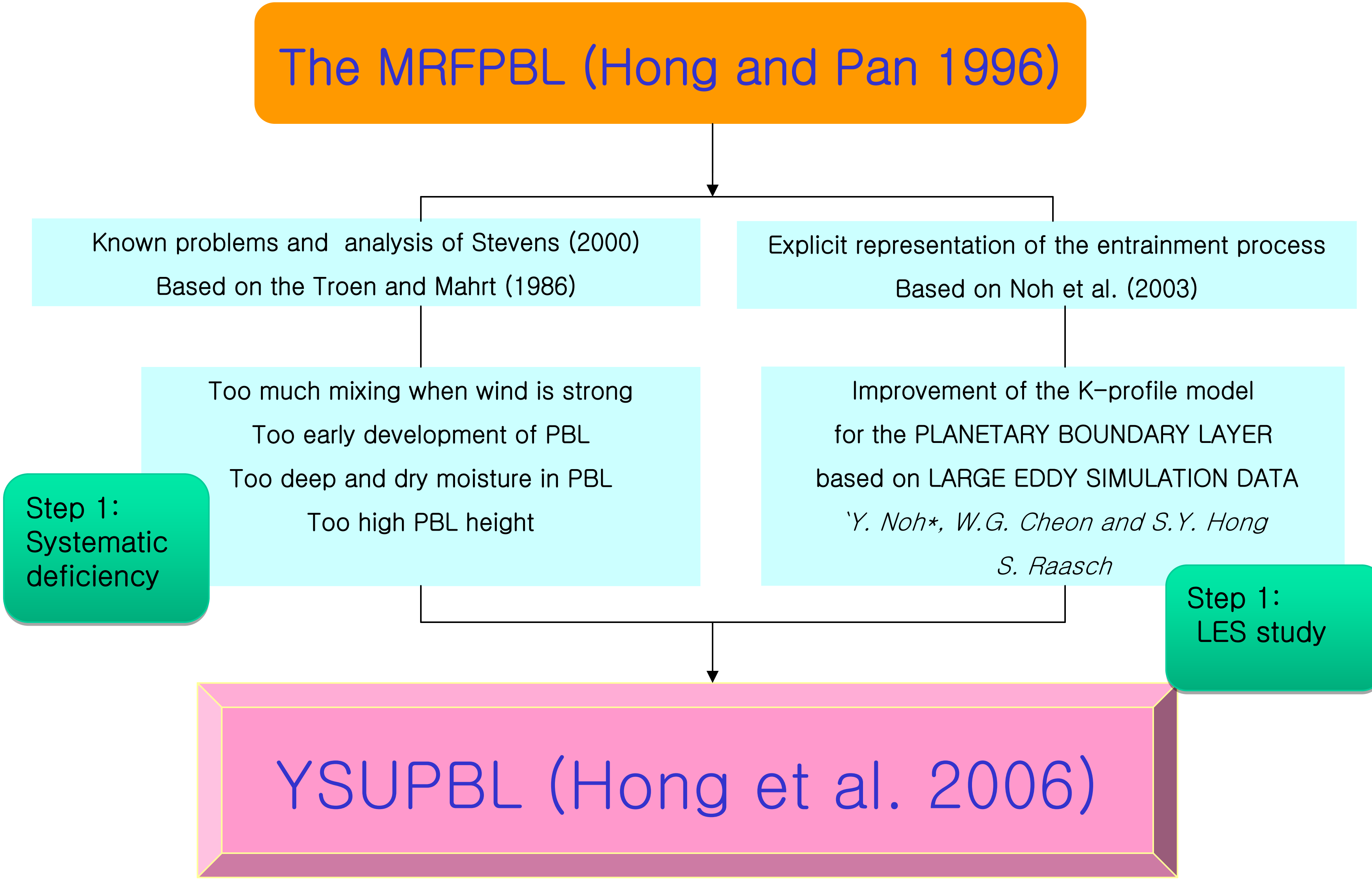
- Systematic deficiency
- LES study/ theory
- Numerical discretization
- Idealized experiments

- Balance with nature (module) : Step 2

- Real case experiments
- Process study
- Refinement/reformulation

- Evaluation at real-time testbed (package) : Step 3

- Short-range forecast
- Medium-range forecast
- Long-range forecast


The MRFPBL (Hong and Pan 1996)
Known problems and analysis of Stevens (2000)
Based on the Troen and Mahrt (1986)
Explicit representation of the entrainment process
Based on Noh et al. (2003)
Too much mixing when wind is strong
Too early development of PBL
Too deep and dry moisture in PBL
Too high PBL height
Step 1: Systematic deficiency
Improvement of the K-profile model
for the PLANETARY BOUNDARY LAYER
based on LARGE EDDY SIMULATION DATA
'Y. Noh*, W.G. Cheon and S.Y. Hong
S. Raasch
Step 1: LES study
YSUPBL (Hong et al. 2006)

YSUPBL - development

Step1

- **2000.9-2001.3** — To formulate a theory (LES→ a new conceptual model)
- **2001.3-2002.7** — To develop a new numerical scheme (PDE → FDE)

Step2 / Step3

- **2002.9-2003.6** — To evaluate the scheme and balance with nature (A new package)
- **2003.7-2004.2** — To revised the scheme based on the various evaluations (A revised new package)
- **2006.2** — Further revisions (A finalized new package)

Stable boundary layer mixing in a vertical diffusion package

Step 1 : Systematic deficiency

- YSU underestimates the chemical species in stable conditions (over water)

Stable BL in YSU PBL (WRF 2.2) : Local approach

$$K_{m\_loc,t\_loc} = l^2 f_{m,t}(Rig)\left(\frac{\partial U}{\partial z}\right) \qquad Rig = \frac{g}{\theta_v}\left[\frac{\partial\theta_v / \partial z}{(\partial U / \partial z)^2}\right] \qquad \frac{1}{l} = \frac{1}{kz} + \frac{1}{\lambda_0}$$

May be inappropriate

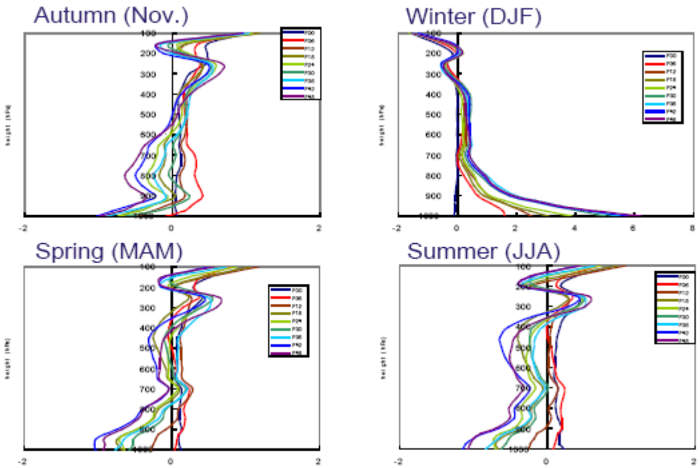
Step 1 : Systematic deficiency

Dear Dr. Hong,

This is Fred. I started to use the fully coupled chemistry within the WRF (WRF/Chem) since I came to Los Alamos to examine the transport and transformation of gaseous and particulate pollutions emitted by megacities such as Mexico City on local and regional scales. One thing I have noticed is that the nocturnal PBL heights in WRF using YSU scheme are nearly constant between 0 and 20 meters. Lidar data from the recent Mexico City field campaign reveal nocturnal PBL heights actually vary between 20 and 500 meters with strong winds corresponding to large PBL heights. I just attended a workshop in Boulder related with the Mexico City field campaign in which many people expressed their concerns for the nearly constant PBL heights in WRF since realistic PBL heights are important for capturing the transport of chemical species.

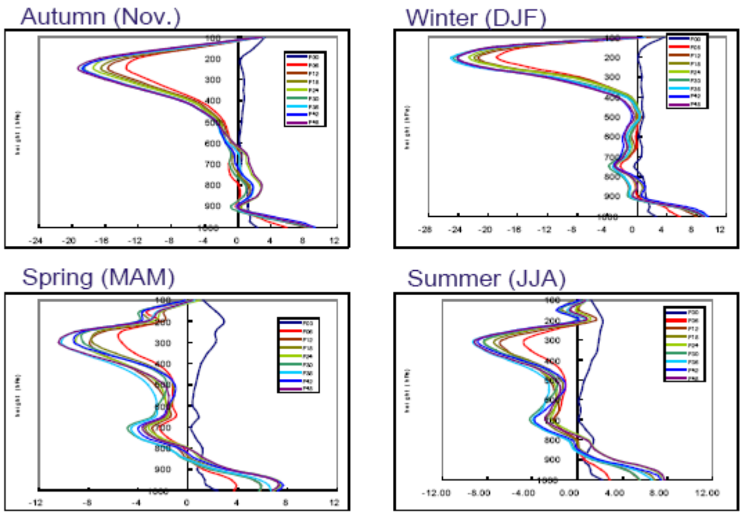
Step 1 : Systematic deficiency

Seasonal Temperature bias of DM1 (from FNL)



- Warm bias appears near surface in winter
- Cold bias appears near surface in the other seasons

Seasonal bias of RH in DM1 (from FNL)



- Wet bias appears near surface in all seasons

WRF real-time operation at JHWC-GPP

Cold and wet biases

Step 1 : Form a new concept

Vickers and Mahrt (2004, BLM, 1736-1749)

$$Rib = h\left(\frac{g}{\overline{\overline{\theta}}}\right)\frac{\left[\theta(h)-\theta_s\right]}{U(h)^2}$$

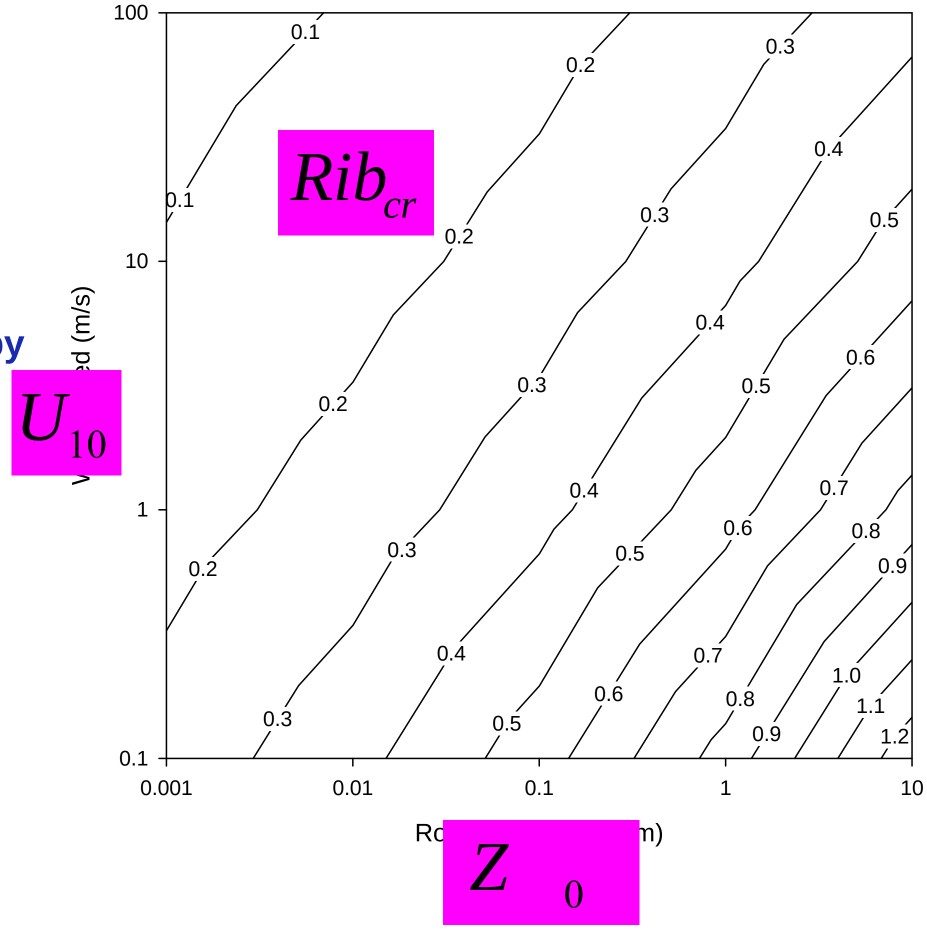
the surface bulk Richardson number
where the critical value for Rib is defined by

$$Rib_{cr} = 0.16\left(10^{-7}R_o\right)^{-0.18}$$

, where

$$R_o = U_{10}/\left(fz_0\right)$$

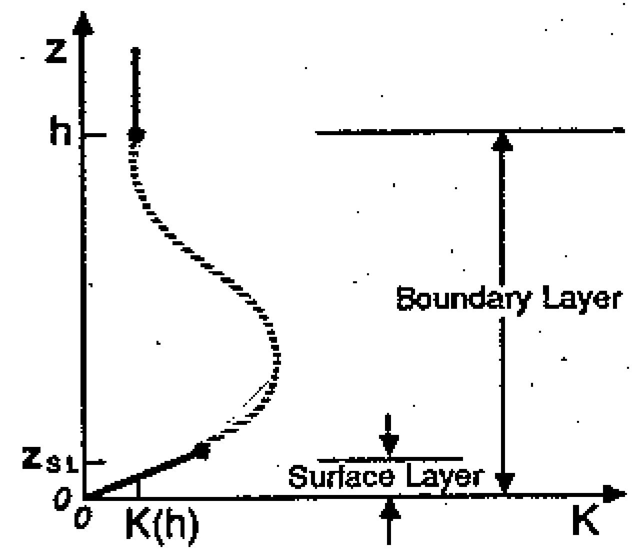
with f=10**-4.



Step 1 : Design a new algorithm

Bulk Ri number approach

$$Ri = \frac{g(\theta_v(h) - \theta_s)}{\theta_{va} \, |U(h)|^2} z$$



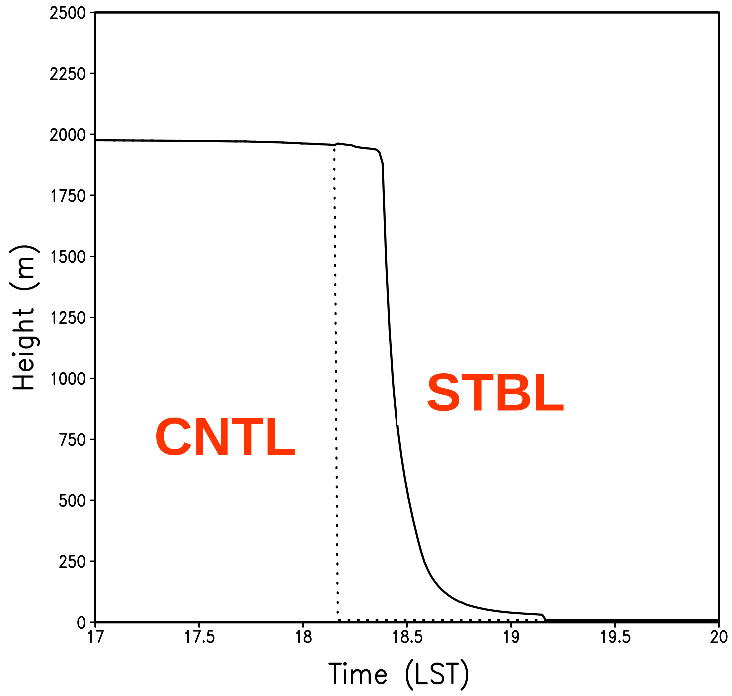
Over water $Rib_{cr} = 0.16\left(10^{-7} R_o\right)^{-0.18}$

Over land $Rib_{cr} = 0.25$

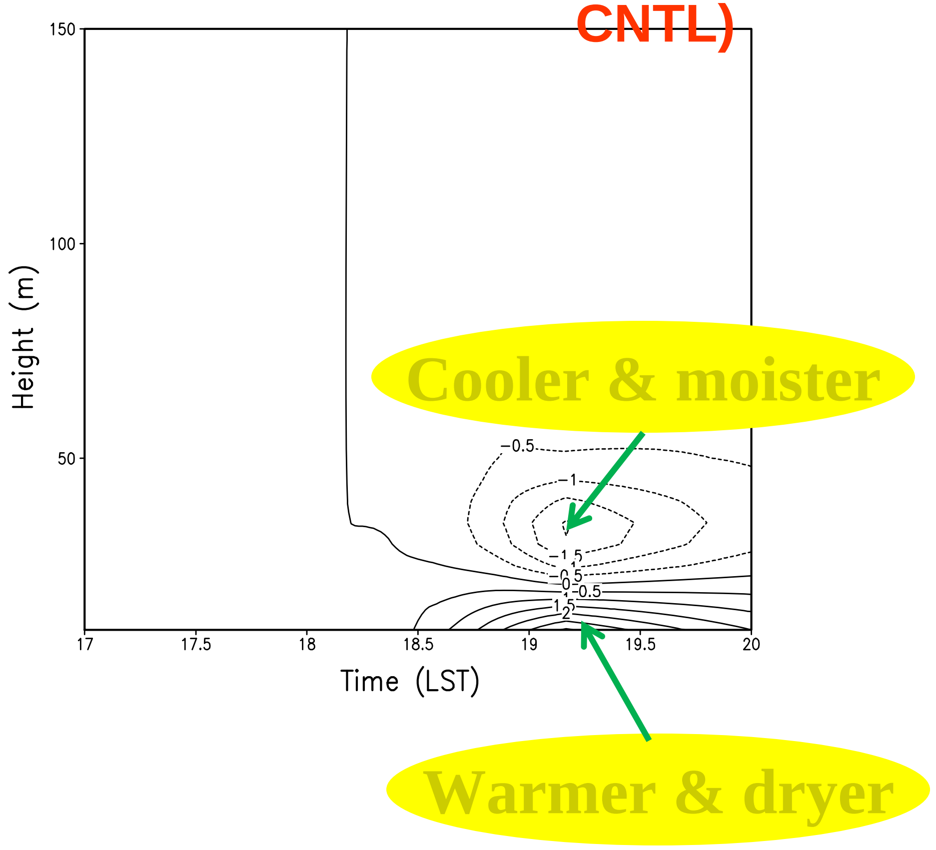
Step 1 : Idealized case

One-d test : dz = 25 m, sunset = 18 h

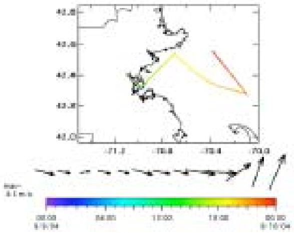
PBL

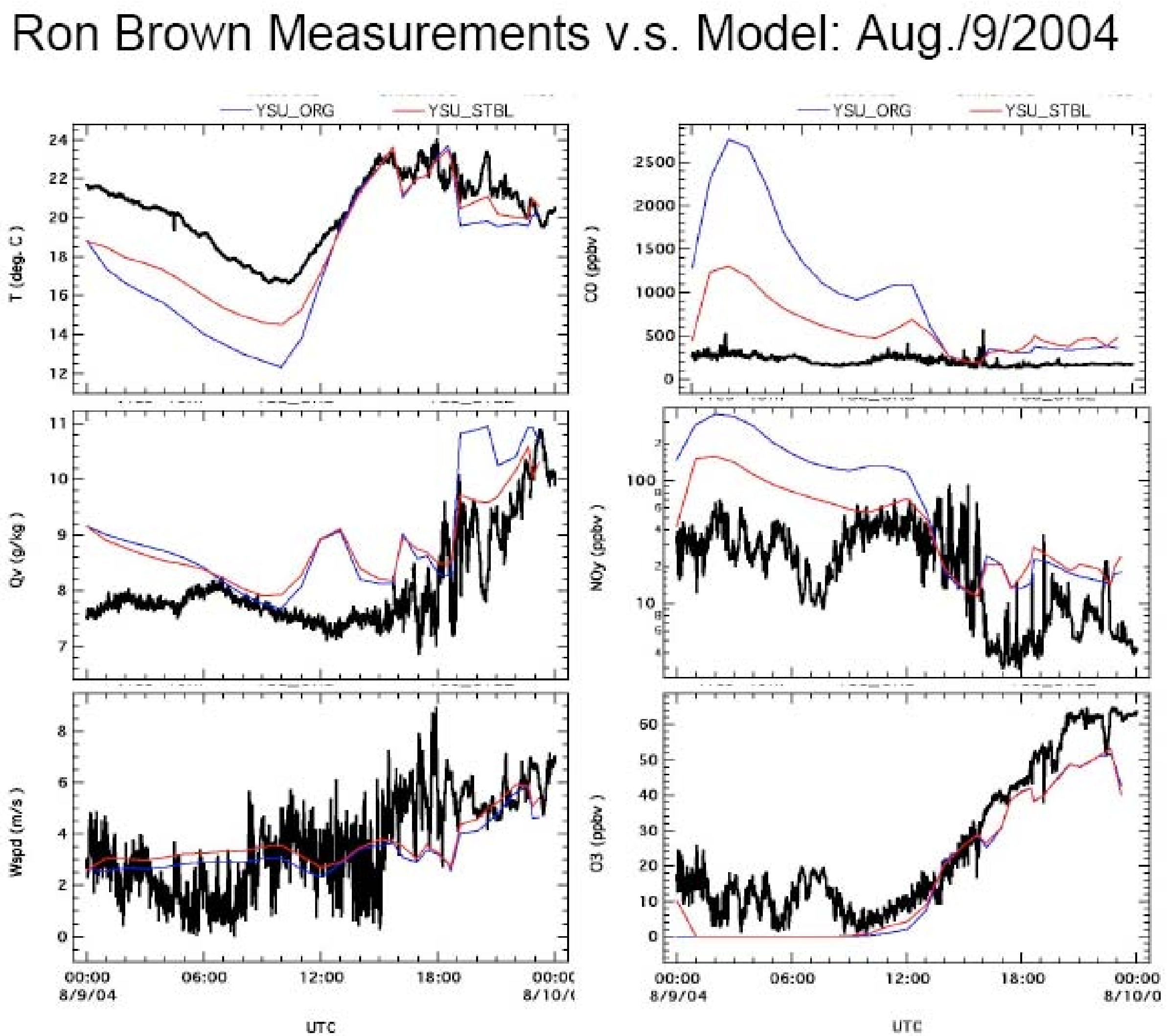


Theta (STBL-CNTL)



Step 2: Real case – Validation with IOP





Black : OBS
Blue : old_STBL
Red : New_STBL

Kim et al. (2008)
WRF workshop

Step 2: Real case-3D

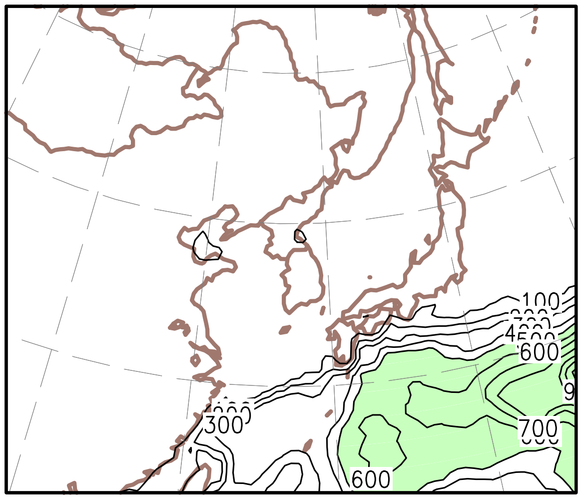
CNTL : Ribcr = 0 (local Ri dependent mixing), WRF 2.2
STBL : Ribcr > 0 (parabolic shape diffusivity), WRF 3.0

Offline test : idealized surface flux forcing
WRF : Cloud resolving resolution (4km)
RSM : Regional climate simulation (50km)
GSM : Seasonal simulation (T62 ~ 200 km)

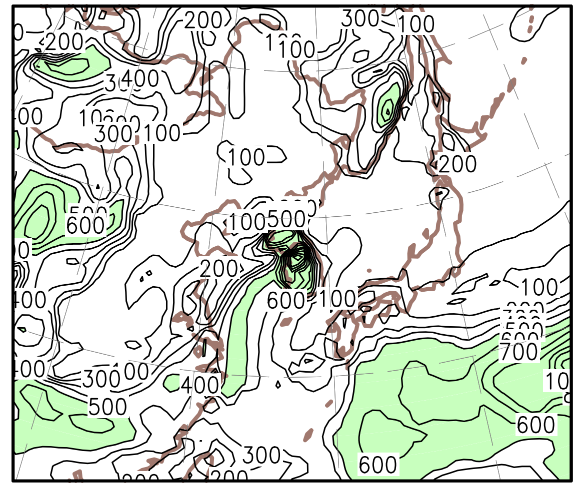
Step 2 : Real case ---- RSM 50 km (18hr fcst)

3 AM

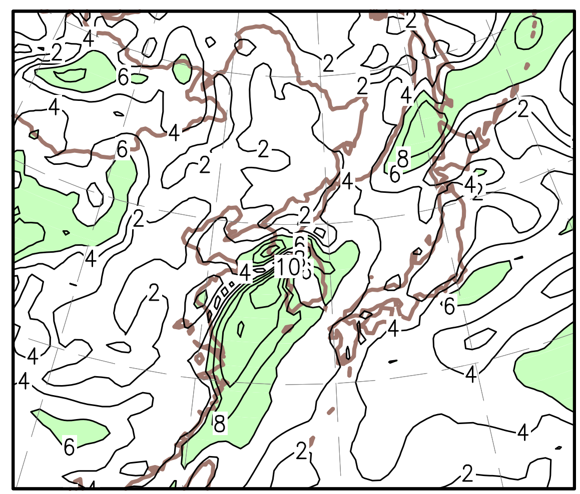
CNTL



STBL



HPBL



10m U

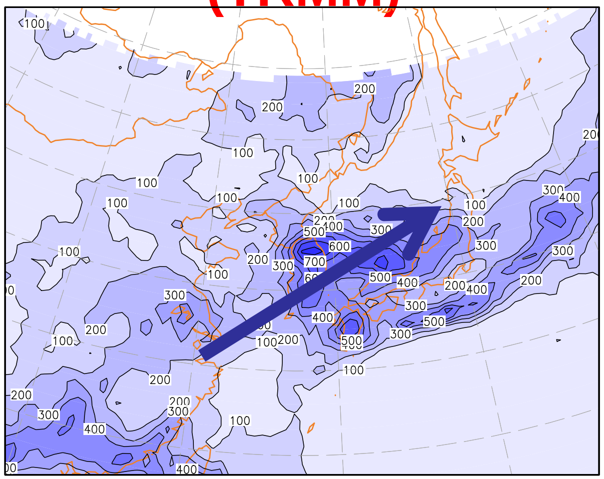
CNTL : PBL height of a constant value during night

STBL : PBL height increases when winds are strong

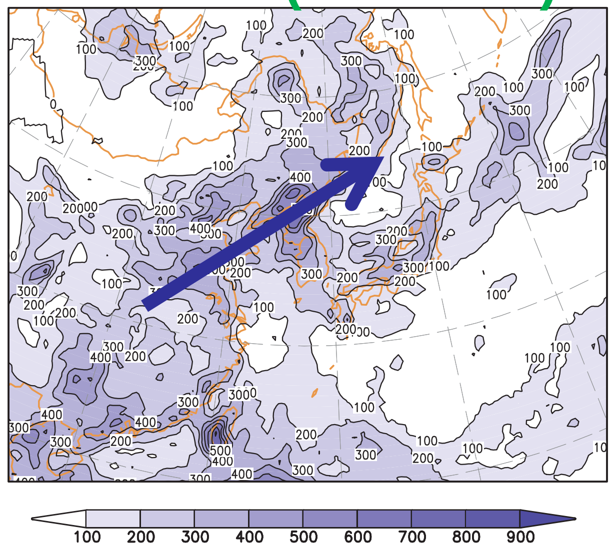
Step 2: Interaction with precipitation – regional

RCM simulation in July 2006: RSM 50 km

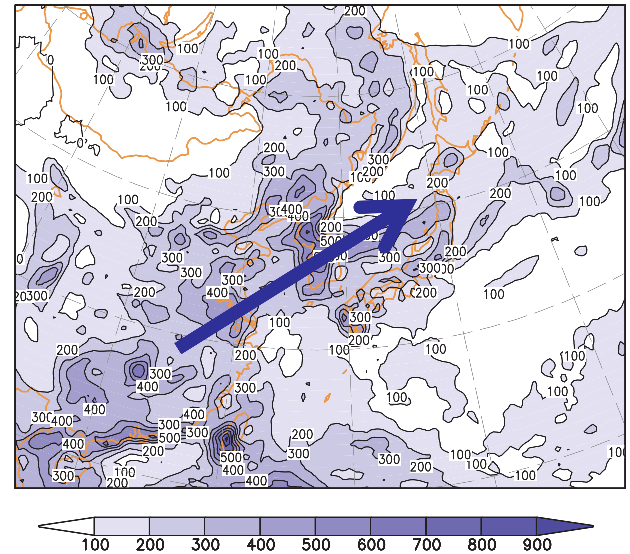
OBS (TRMM)



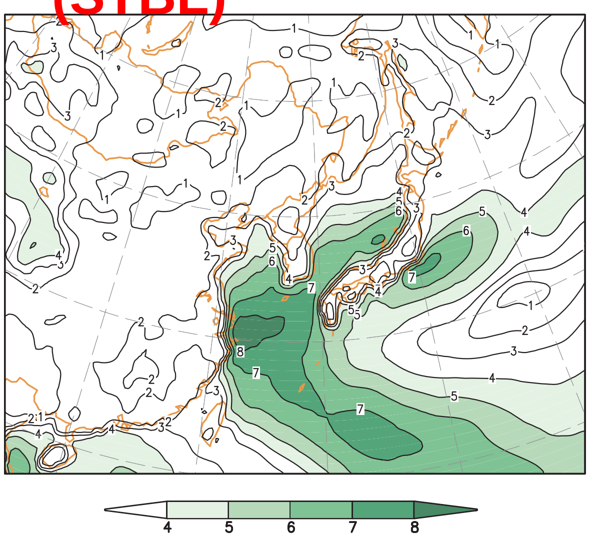
CNTL (PC = 0.47)



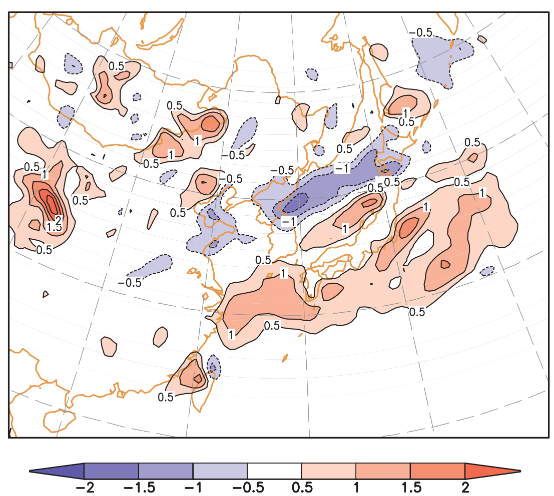
STBL (PC = 0.57)



850 hPa WP (STBL)



STBL-CNTL



Nighttime rainfall is enhanced
Oceanic rainfall is enhanced

Hong (2010 QJRMS)

Step 2: Interaction with other physics

Seasonal simulation (T62; about 200 km)

Model : GRIMs-v2 (Global/Regional Integrated Model system)

Period : 1996. 5 – 8 (JJA), 1996.11-1997. 2 (DJF)

Ensemble : 5 members

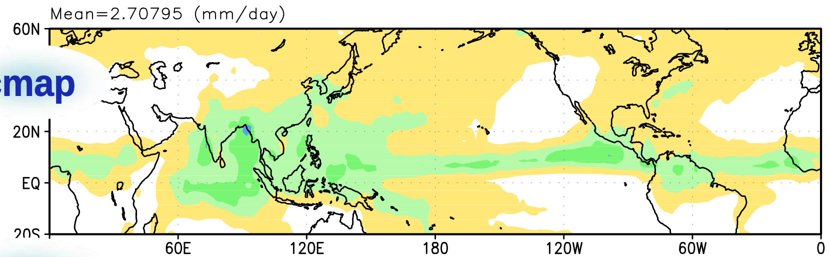
Experiments: CNTL : Hong et al. 2006

STBL : Hong 2010 (enhanced mixing)

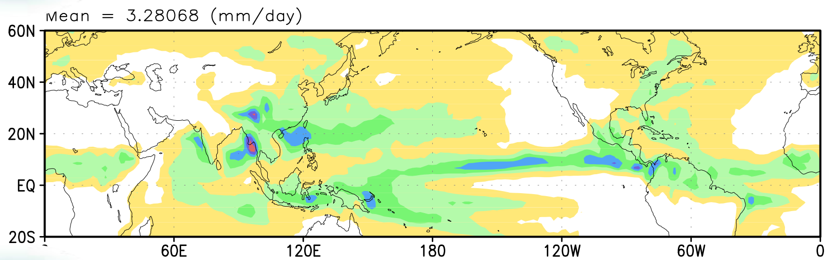
Step 2: Interaction with other physics

Seasonal simulation for JJA 1996 (rainfall)

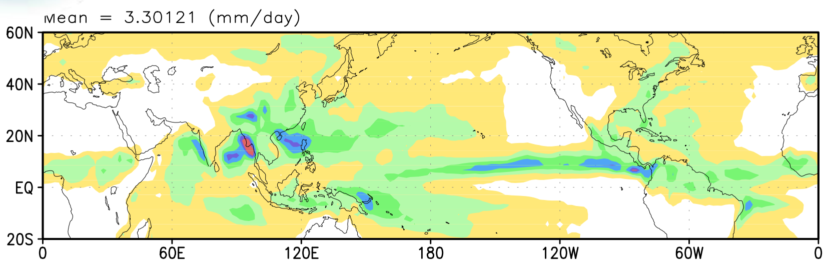
cmap



CNTL



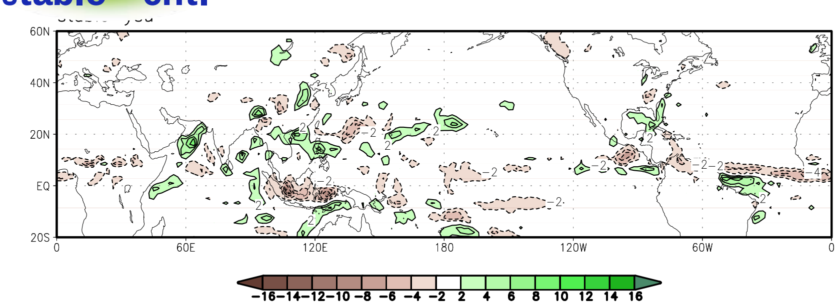
STBL



	ysu	stable	stable_150
Global mean			
OBS	= 2.70795	= 2.70795	= 2.70795
MODEL	= 3.28068	= 3.30121	= 3.31642
Pattern correlation			
GL	= 0.736781	= 0.739652	= 0.738123
EA	= 0.625432	= 0.60589	= 0.678413

Scheme is stable !!!
Skill is comparable

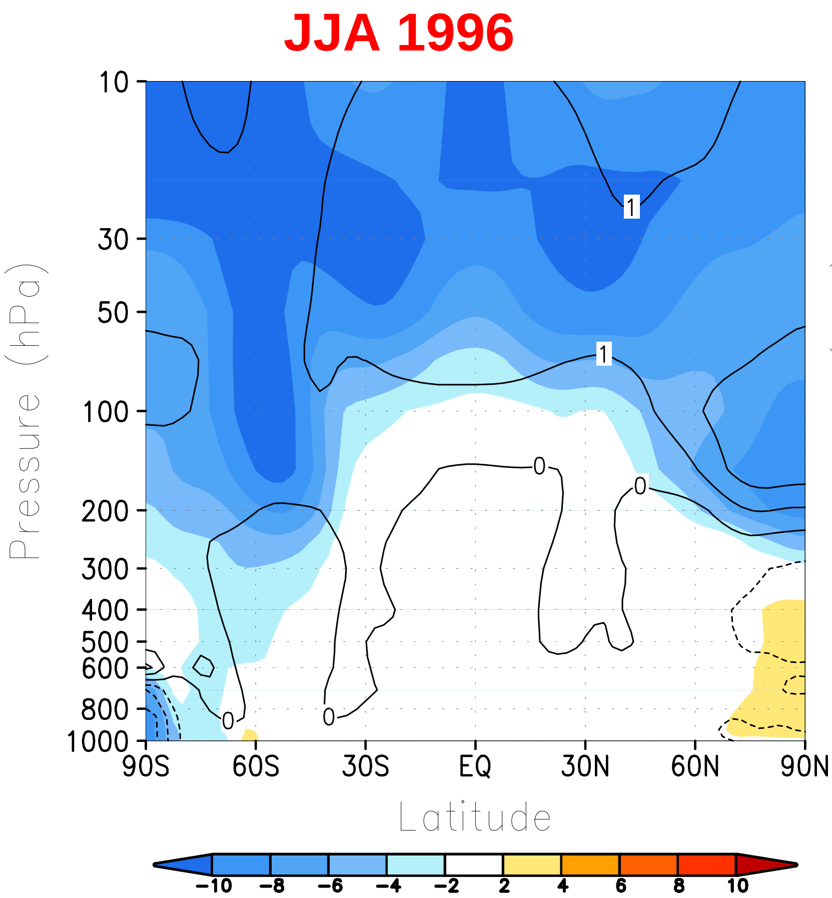
stable - cntl

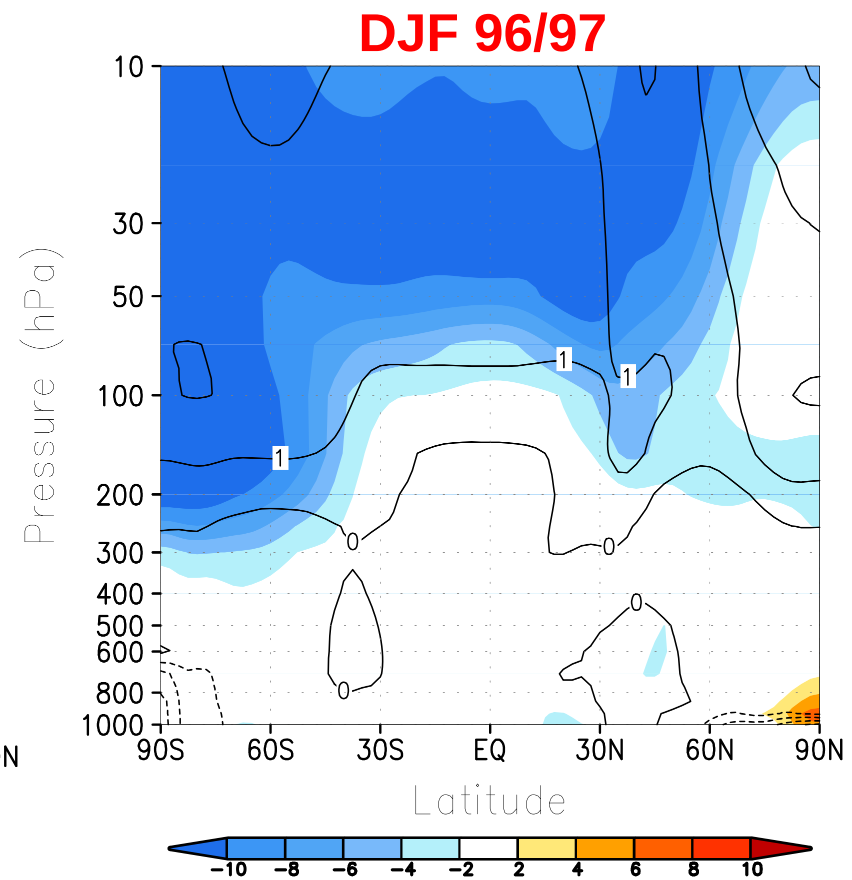


Step 2: Interaction with other physics

Zonal mean temperature

Shaded : CNTL-RA2
Contour : STBL-CNTL





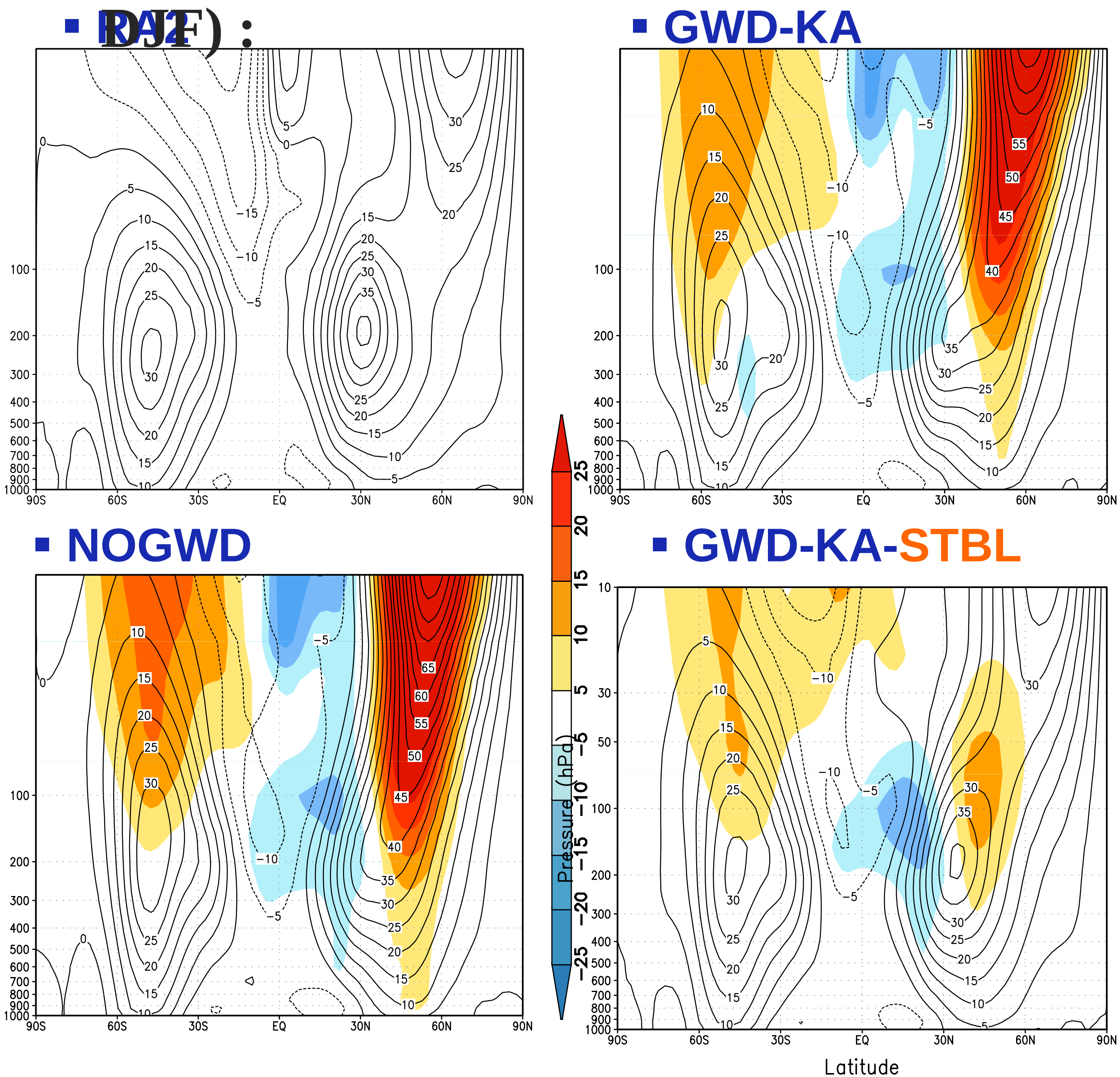
Error is reduced by 10 % due to stable BL

Stable boundary mixing should be confined in the lower troposphere, then, how it influences the stratosphere ???

---- Interaction issue

Step 2: Harmony

Zonal-averaged zonal wind (96/97 DJF) :

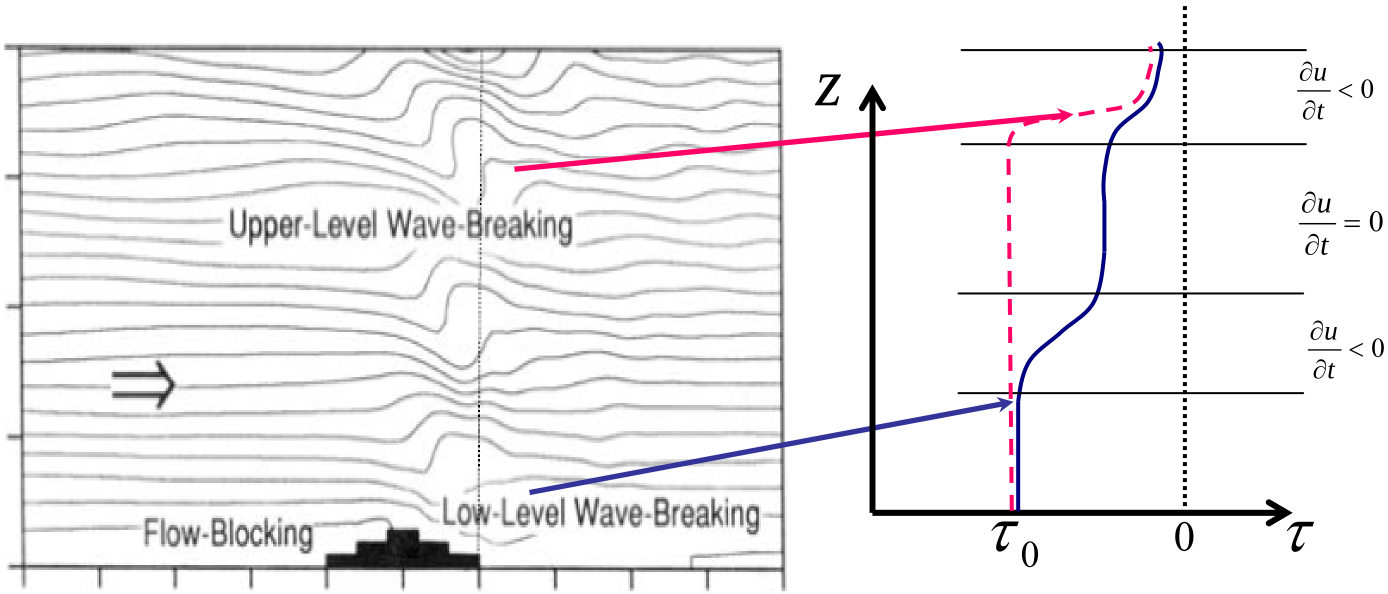


Contour : Zonal averaged zonal wind
Shaded: Deviations from the RA2

Kim and Arakawa
→Improves upper level jets
→Improves the sea level pressure

(Kim and Hong, GR-letter, June 2009)

Enhanced lower tropospheric gravity wave drag
(Kim and Arakawa 1995, J. Atmos. Sci.)



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

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

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

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

OLD SBL : Too shallow PBL height ➔ too small Tau_0 ➔ too small drag in the upper troposphere ➔ too strong westerly bias

Step 3: Short-range forecast : SLP trend

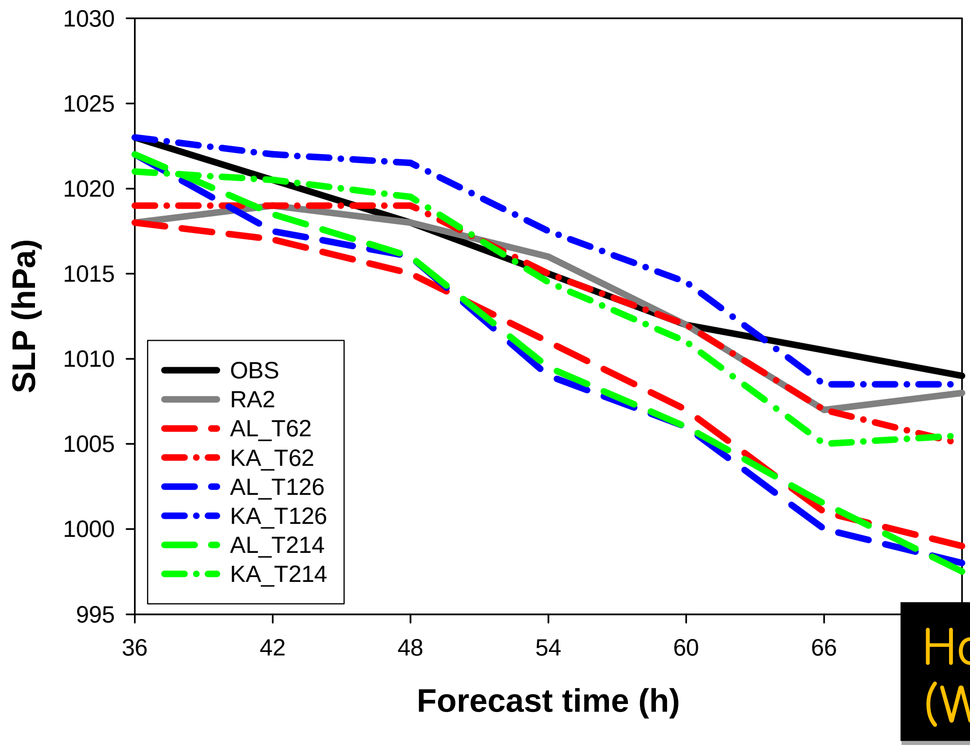
- Error Table

Time	48-h forecast		72-h forecast	
	RMSE	PC	RMSE	PC
NOGWD	2.34	0.89	4.33	0.88
UPGWD	2.23	0.91	4.79	0.85
LOGWD	2.12	0.91	4.28	0.84
LOGWD_KD	2.29	0.93	3.04	0.92
LOGWD_MX	2.19	0.93	2.95	0.92

AL ← UPGWD

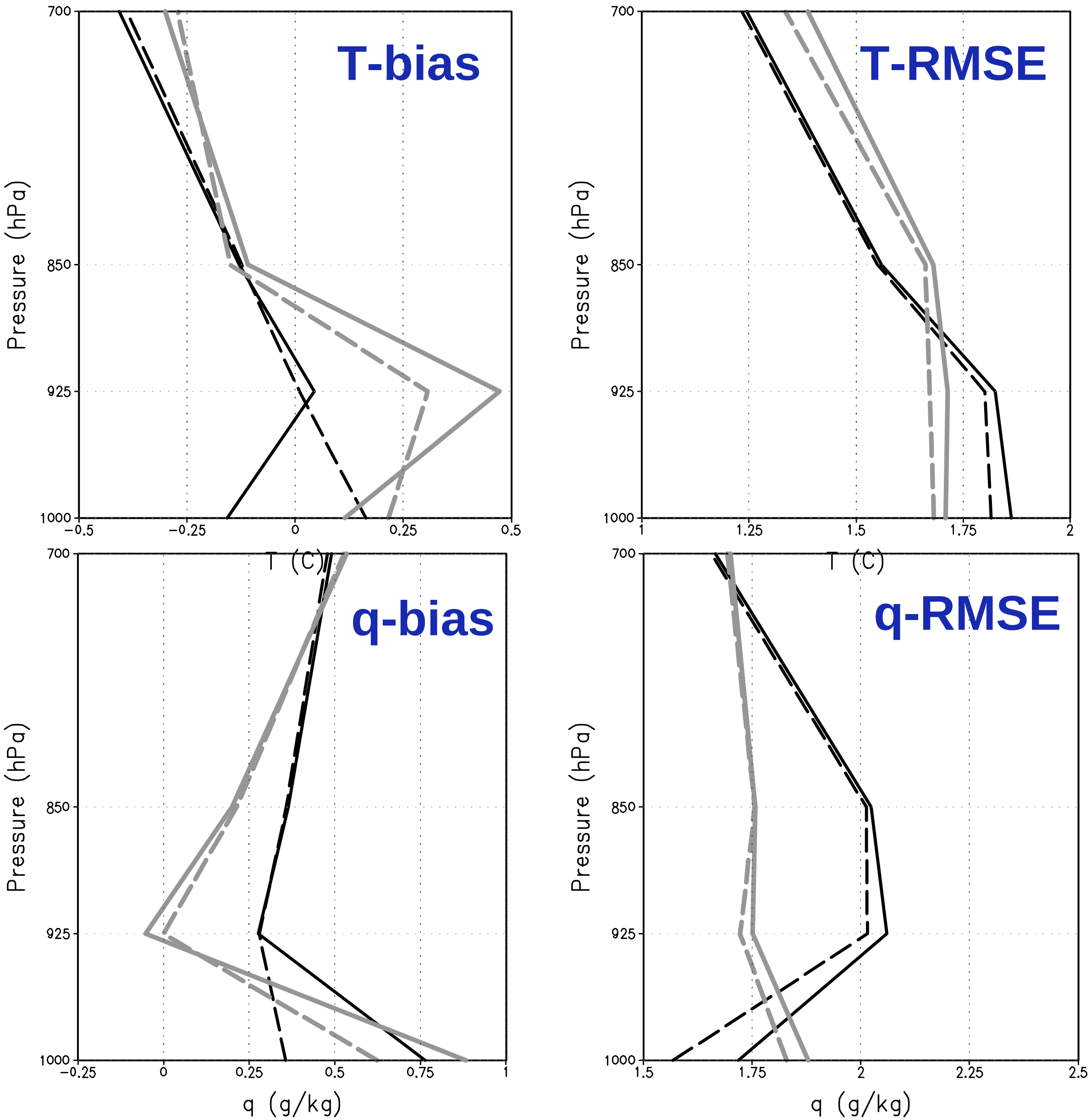
KA ← LOGWD_MX

- Resolution Test



Hong et al. 2008
(Wea Forecasting)

Step 3: A statistical evaluation – July 2006



Solid : CNTL-OBS
Dashed: STBL-OBS

Cold start run : 00 UTC → 48 hr forecasts (31 cases)

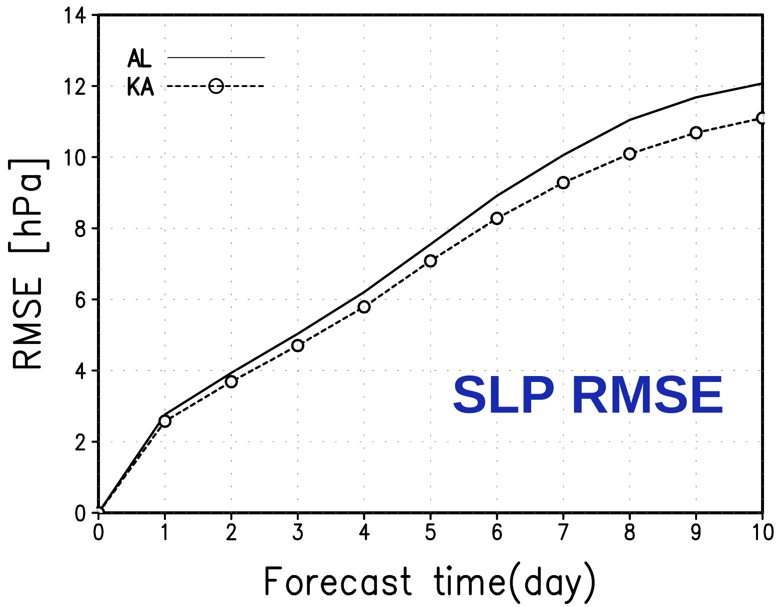
WRF , 50 km over East Asia

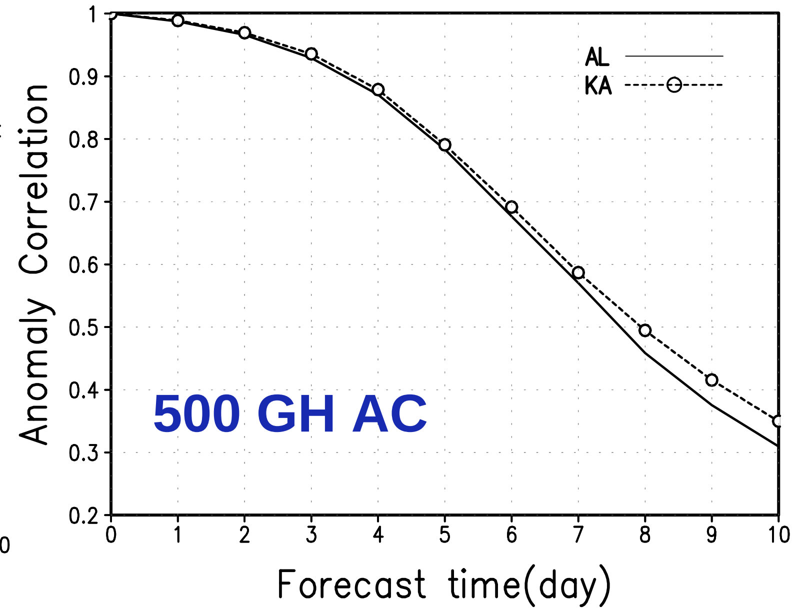
OBS : Radiosonde data

(grey : 12 UTC, black : 00 UTC)

Hong 2010 (QJRMS, in press)

Step 3: Medium-range forecast : December 2006 (10 day run every 00, 12 UTC)





CNTL+KAGWD

STBL+KAGWD

Hong et al. 2008 (Wea Forecasting)

KA 1995 GWDO scheme was correctly devised, but it took another 12 yrs to make it work

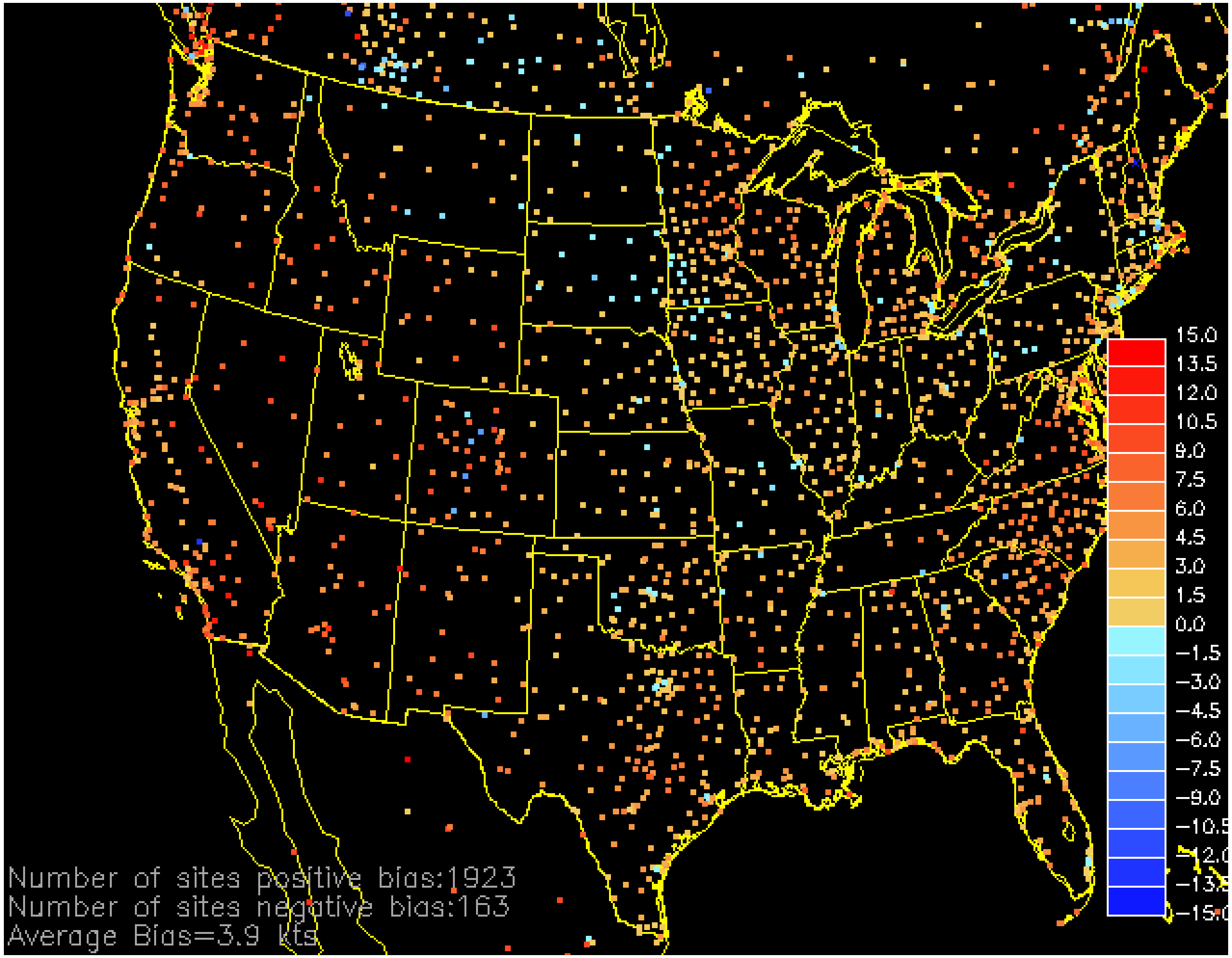
*Initial implementation : 1995
*Final (?) implementation : 2007

YSU PBL finished ???

An apparent systematic bias :

Too strong surface wind in nighttime

AFWA : WRF 6Z Run, 24 Hour Fcst (mid night)
Wind Speed >= 10kts

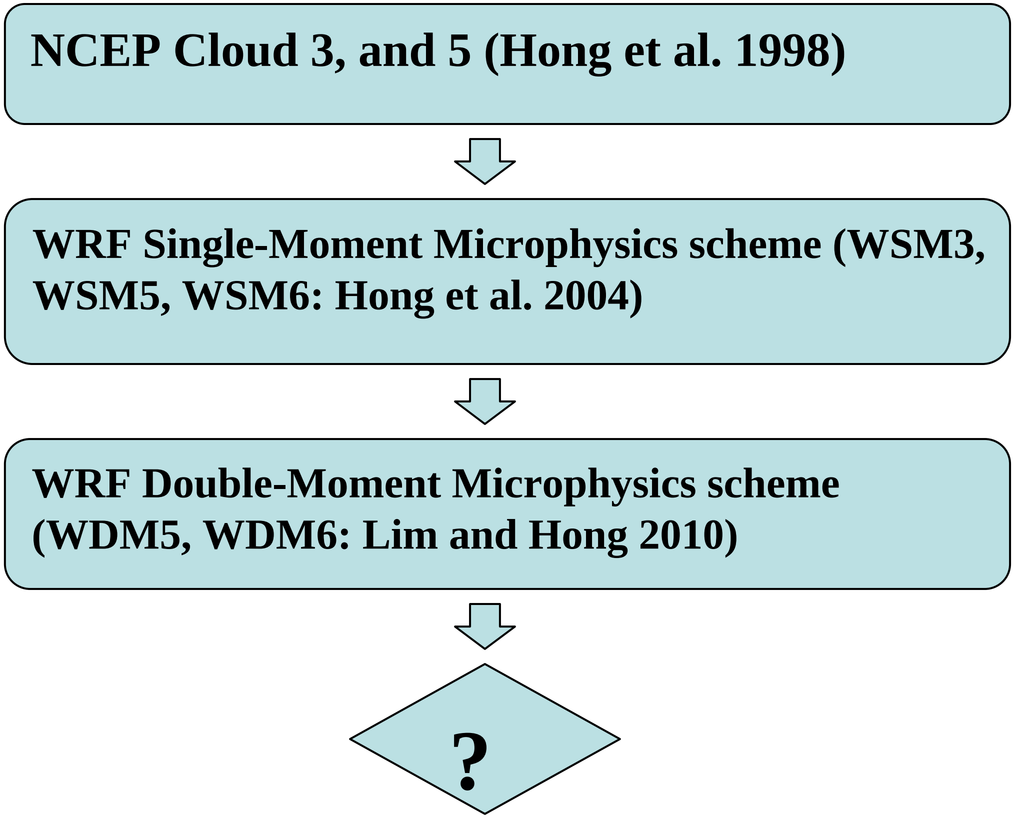


Some issues in PBL (NWP perspective)

Current status
- PBL structure in daytime is relatively well simulated
- PBL mixing in nighttime stable regime is generally weak
- Temperature is good, moisture is not bad, but winds bad
- PBL in precipitating convection is poorly understood

Further development
- Hybrid approach combining the non-local and TKE (HD PBL)
- Understanding the moist PBL turbulence
- Interaction with other physical processes
- Super-parameterization (nesting LES model in vertical)

The same strategy has been applied to other physics algorithms. For example,



Current issues in model physics

Lee and Hong (2005, BAMS)

PHYSICAL PARAMETERIZATION IN NEXT-GENERATION NWP MODELS

BY TAE-YOUNG LEE AND SONG-YOU HONG

The Second International Workshop on Next-Generation Numerical Weather Prediction (NWP) Models[1] met to discuss the impact of recent developments in modeling for next-generation, high-resolution NWP models, and to exchange ideas for improving the prediction of high-impact weather. In 1999, the Laboratory for Atmospheric Modeling Research (LAMOR) of Yonsei University (YSU) embarked on a national project developing a next-generation NWP model focusing on the parameterization of physical processes in high-resolution models (see information online at http://lamor.yonsei.ac.kr). The ultimate goal of the project is in line with that of the Weather Research and Forecast (WRF) model initiative (see information online at http://wrf-model.

THE SECOND INTERNATIONAL WORKSHOP ON NEXT-GENERATION NWP MODELS

WHAT: Scientists from Korea, Japan, and the United States discuss recent developments in the parameterizations of physical processes in next-generation, high-resolution numerical weather prediction models

WHEN: 17–18 May 2004

WHERE: Yonsei University, Seoul, Korea

The director of LAMOR, Professor Tae-Young Lee, told participants that the focus of this workshop was

PROBLEMATIC ISSUES. Problems with physics parameterizations in the models that emerged during the workshop include the following: resolution dependency of each physical process, deterministic versus stochastic approaches, and use of observations.

Resolution dependency of physics. Physical parameterization schemes developed at one scale may no longer be valid at smaller scales, because computer power increases and grid sizes decrease. Cumulus schemes are a current example, and PBL schemes may be

Deterministic versus ensemble versus stochastic approaches. Deterministic approaches to modeling imply refinement of parameterizations, addition of complexity, and superparameterization, whereas an ensemble approach can be based on uncertainties in initial conditions or physics schemes. Meanwhile, stochastic approach incorporates randomness, such as Grell's ensemble cumulus approach, the PDF approach, or random number uses. For a given

Use of observations. The increase of various observations may not guarantee the improvement of model forecasts. Many observation datasets are not useful from a point of view of modeling, and/or are not obtained with the purpose of improving model per-

Dynamics versus Physics

Dynamics is accurate but physics is muddy ?

Deterministic approach is saturated ?

Accurate refinement in model is being saturated ?

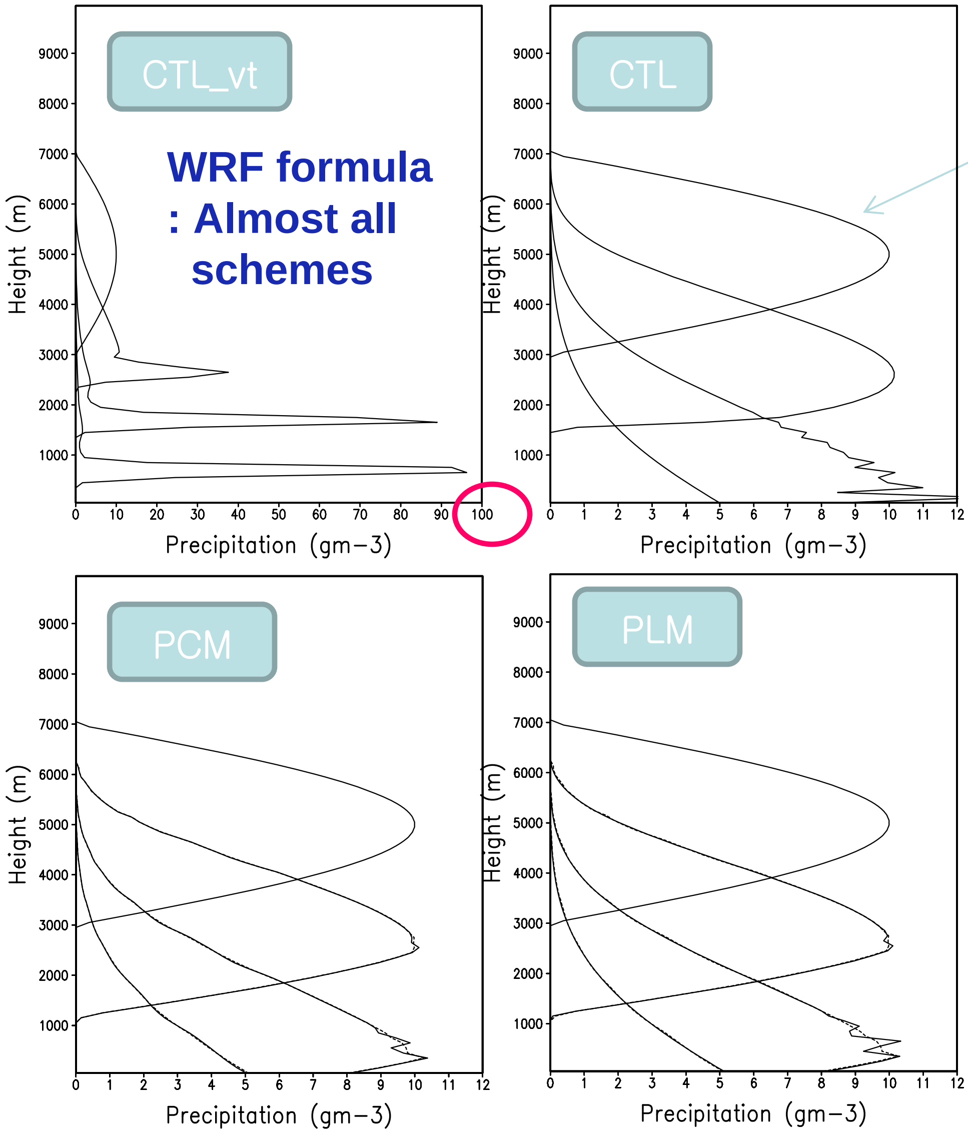
Forward semi-Lagrangian mass conservation positive definite advection scheme for sedimentation of precipitation

Hann-Ming Henry Juang and Song-You Hong

(Mon Wea Rev, 2010 May issue)

WSM3 implementation : 1D case

❖Evolution of Hydrometeors



Hydrometeor Shape at initial time
qr = 10 cos[pi (Zc-Z)/Zd] (g/kg)

dz=100m, Zc=5000, Zd=40dz

Terminal velocity is function of qr

$$V_G[\mathrm{ms}^{-1}] = \frac{a_G \Gamma(4+b_G)}{6}\left(\frac{\rho_o}{\rho}\right)^{\frac{1}{2}} \frac{1}{\lambda_G^{b_G}}$$

Maxima W is about 10 m/s
dt=120s CFL=10*120/100 = 12

Current sedimentation in WRF (CTL_vt) : A serious problem

SEMI with PLM is a good choice

Dynamics versus Physics

It is interesting to note that the ill-posed sedimentation in NWP models has been placed for more than 20 yrs

Much efforts has been given to microphysics itself

Hopefully this is the final, but they may be another or many

Resolution dependency

Cut-off horizontal grid length for parameterizations

- Cumulus parameterization : ~ 3 km (Shin and Hong 2009)
- PBL : ~50 m (Mirocha, 2008 WRF workshop)
- GWDO : ~ 3 km (hydrostatic approximation)
- GWDC: ~ 3 km (go with CP)

- However, recall the past 20 years

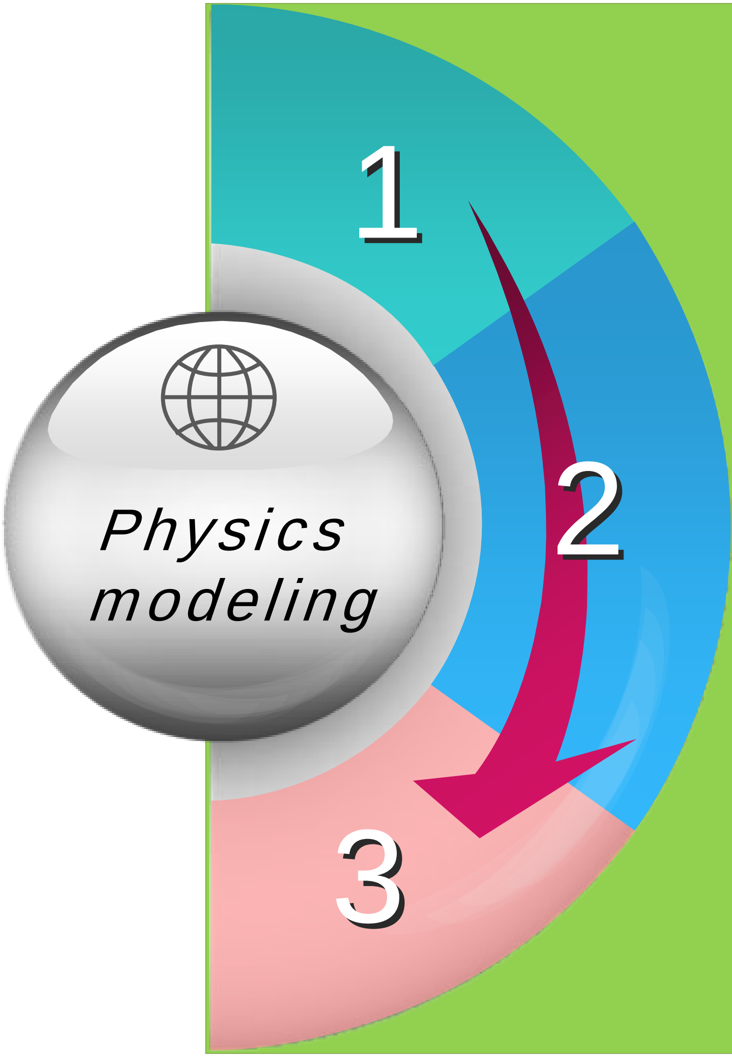
Resolution dependency

Cut-off horizontal grid length for Cumulus parameterization :

- KMA regional prediction model has been operational without CP even at 80 km until late 1990
- With advances in CP and other physics and initial condition, the cut-off length becomes smaller and smaller
- CP is beneficial even at 4 km (JMA operational model)

Subgrid-scale parameterization for physics may be necessary even at 1 km or smaller since the finite model grid cannot resolve all the nature explicitly

Progress and Prospects



1. Deterministic approach

a) Convectional method :

- Simplified Arakawa-Schubert [SAS] (Numagtuti et al. 1995)
- Kuo scheme (Kuo 1974)
- Relaxed Arakawa-Schubert [RAS] (Moorthi and Suarez, 1992)

b) Superensemble method (Krishnamurti and Sanjay 2003)

- weighted average of products from 6 different convective schemes

2. Stoachstic approach

• Houtekamer et al. (1996)

: to mimic the parameterization error by using different parameterizations within ensemble prediction system

• Buizza et al. (1999)

: to impose a stochastic term to the physical parameterization (European Centre for Medium-Range Weather Forecasts Ensemble Prediction System)

• Grell and Devenyi (2002) : designed by a random multiplier

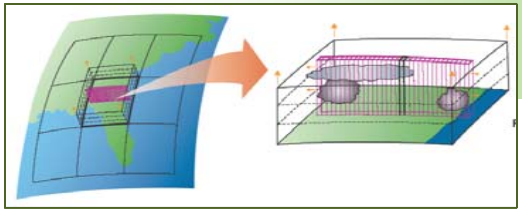
• Lee et al. (2008) : unified multicumulus convective ensemble

3. Intergrated approach

• Byun and Hong (2007) : Cumulus convection organized by synoptic scale moisture convergence (dynamics→ physics)

Progress and Prospects

- Convectional method
- (↓) Superparameterization method



Deterministic approach

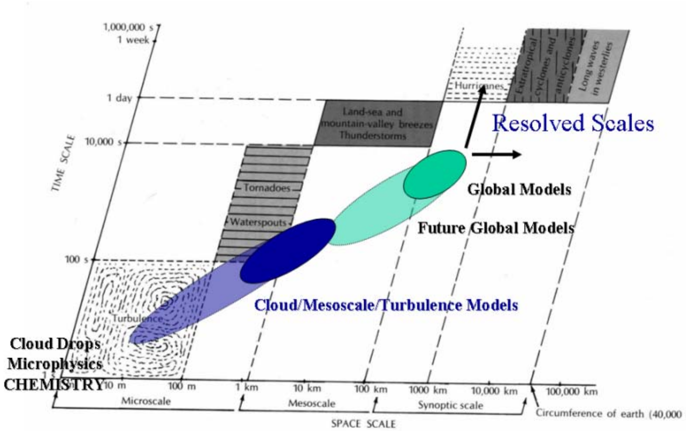
Physics modeling

- stochastically-forced deterministic representation of atmospheric phenomena

Stoachastic approach

- integrated representation of physical processes to remove undesirable noise-generating waves

Integrated approach



Models due to the resolution and physics parameterizations

Unknown versus Uncertain

One should apply the stochastic method to uncertain process

One should find a deterministic solution for unknown process

Development strategy

Physically based

Simplicity

Harmony

Final remarks

Evaluation is everything ~~~

but critical to yourself !!!

[Code Description]

Weather Research and Forecasting (WRF) Double-Moment 6-class (WDM6) Microphysics scheme

Numerical Modeling Laboratory, Yonsei University (YSU)

WRF Model Structure

SUBROUTINE module_physics_init.F

CALL wdm6init

SUBROUTINE microphysics_driver.F

CALL wdm6

DO j = jts, jte
CALL **wdm62D**
ENDDO

module_mp_wd

SUBROUTINE wdm6

SUBROUTINE **wdm62D**

REAL FUNCTION rgmma(x)

REAL FUNCTION fpvs

SUBROUTINE wdm6init

Structure of wdm62D

$N_{step} = \Delta t / \Delta t_{cld\_max}$

$N_{sed} = V_N \Delta t_{cld} / \Delta Z$

N_R Sedimentation

$N_{sed} = V_q \Delta t_{cld} / \Delta Z$

q_R, q_S, and q_G Sedimentation

Melting of snow/graupel

$N_{sed} = V_q \Delta t_{cld} / \Delta Z$

q_I Sedimentation

Surface precipitation calculation

Calculate other production terms due to Microphysical processes (Warm rain/Cold rain processes)

Update variables (qv, qc, qi, qr, qs, qg, Nccn, Nc, Nr, T)

Nucleation/Condensation

module_mp_wd

```
MODULE module_mp_wdm6
!
!
!
   REAL, PARAMETER, PRIVATE :: dtcldcr     = 120.  ! maximum time step for minor loops
   REAL, PARAMETER, PRIVATE :: n0r = 8.e6          ! intercept parameter rain
   REAL, PARAMETER, PRIVATE :: n0g = 4.e6          ! intercept parameter graupel
   REAL, PARAMETER, PRIVATE :: avtr = 841.9        ! a constant for terminal velocity of rain
   REAL, PARAMETER, PRIVATE :: bvtr = 0.8          ! a constant for terminal velocity of rain
   REAL, PARAMETER, PRIVATE :: r0 = .8e-5          ! 8 microm  in contrast to 10 micro m
   REAL, PARAMETER, PRIVATE :: peaut = .55         ! collection efficiency
   REAL, PARAMETER, PRIVATE :: xncr = 3.e8         ! maritime cloud in contrast to 3.e8 in tc80
   REAL, PARAMETER, PRIVATE :: xmyu = 1.718e-5     ! the dynamic viscosity kgm-1s-1
   REAL, PARAMETER, PRIVATE :: avts = 11.72        ! a constant for terminal velocity of snow
   REAL, PARAMETER, PRIVATE :: bvts = .41          ! a constant for terminal velocity of snow
   REAL, PARAMETER, PRIVATE :: avtg = 330.         ! a constant for terminal velocity of graupel
   REAL, PARAMETER, PRIVATE :: bvtg = 0.8          ! a constant for terminal velocity of graupel
   REAL, PARAMETER, PRIVATE :: deng = 500.         ! density of graupel
   REAL, PARAMETER, PRIVATE :: n0smax =  1.e11     ! maximum n0s (t=-90C unlimited)
   REAL, PARAMETER, PRIVATE :: lamdacmax = 1.e10   ! limited maximum value for slope parameter of cloud water
   REAL, PARAMETER, PRIVATE :: lamdarmax = 1.e8    ! limited maximum value for slope parameter of rain
   REAL, PARAMETER, PRIVATE :: lamdasmax = 1.e5    ! limited maximum value for slope parameter of snow
   REAL, PARAMETER, PRIVATE :: lamdagmax = 6.e4    ! limited maximum value for slope parameter of graupel
   REAL, PARAMETER, PRIVATE :: dicon = 11.9        ! constant for the cloud-ice diamter
   REAL, PARAMETER, PRIVATE :: dimax = 500.e-6     ! limited maximum value for the cloud-ice diamter
   REAL, PARAMETER, PRIVATE :: n0s = 2.e6          ! temperature dependent intercept parameter snow
   REAL, PARAMETER, PRIVATE :: alpha = .12         ! .122 exponen factor for n0s
   REAL, PARAMETER, PRIVATE :: pfrz1 = 100.        ! constant in Biggs freezing
   REAL, PARAMETER, PRIVATE :: pfrz2 = 0.66        ! constant in Biggs freezing
   REAL, PARAMETER, PRIVATE :: qcrmin = 1.e-9      ! minimun values for qr, qs, and qg
   REAL, PARAMETER, PRIVATE :: ncmin = 1.e1        ! minimum value for Nc
   REAL, PARAMETER, PRIVATE :: nrmin = 1.e-2       ! minimum value for Nr
   REAL, PARAMETER, PRIVATE :: eacrc = 1.0         ! Snow/cloud-water collection efficiency
   REAL, PARAMETER, PRIVATE :: dens  =  100.0      ! Density of snow
   REAL, PARAMETER, PRIVATE :: qs0   =  6.e-4      ! threshold amount for aggretion to occur
!
   REAL, PARAMETER, PRIVATE :: satmax = 1.0048     ! maximum saturation value for CCN activation
                                                   ! 1.008 for maritime /1.0048 for conti
   REAL, PARAMETER, PRIVATE :: actk = 0.6          ! parameter for the CCN activation
   REAL, PARAMETER, PRIVATE :: actr = 1.5          ! radius of activated CCN drops
   REAL, PARAMETER, PRIVATE :: ncrk1 = 3.03e3      ! Long's collection kernel coefficient
   REAL, PARAMETER, PRIVATE :: ncrk2 = 2.59e15     ! Long's collection kernel coefficient
   REAL, PARAMETER, PRIVATE :: di100 = 1.e-4       ! parameter related with accretion and collection of cloud drops
   REAL, PARAMETER, PRIVATE :: di600 = 6.e-4       ! parameter related with accretion and collection of cloud drops
   REAL, PARAMETER, PRIVATE :: di2000 = 2000.e-6   ! parameter related with accretion and collection of cloud drops
   REAL, PARAMETER, PRIVATE :: di82    = 82.e-6    ! dimater related with raindrops evaporation
   REAL, PARAMETER, PRIVATE :: di15    = 15.e-6    ! auto conversion takes place beyond this diameter
!
```

m6.F

**Tunable parameters

SUBROUTINE wdm6

```
DO j = jts, jte
    CALL wdm62D
ENDDO
```

```
! 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  [CP 17]
!        (C->R)
!-------------------------------------------------------------
          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 [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       [CP 22 & 23]
!        (C->R)
! nracw: accretion of cloud water by rain
!        (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
```

** Warm rain processes (Hong and Lim 2010)

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

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

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

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

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

$D_R \geq 100$ μm

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

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

$D_R < 100$ μm

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

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


Thank you !

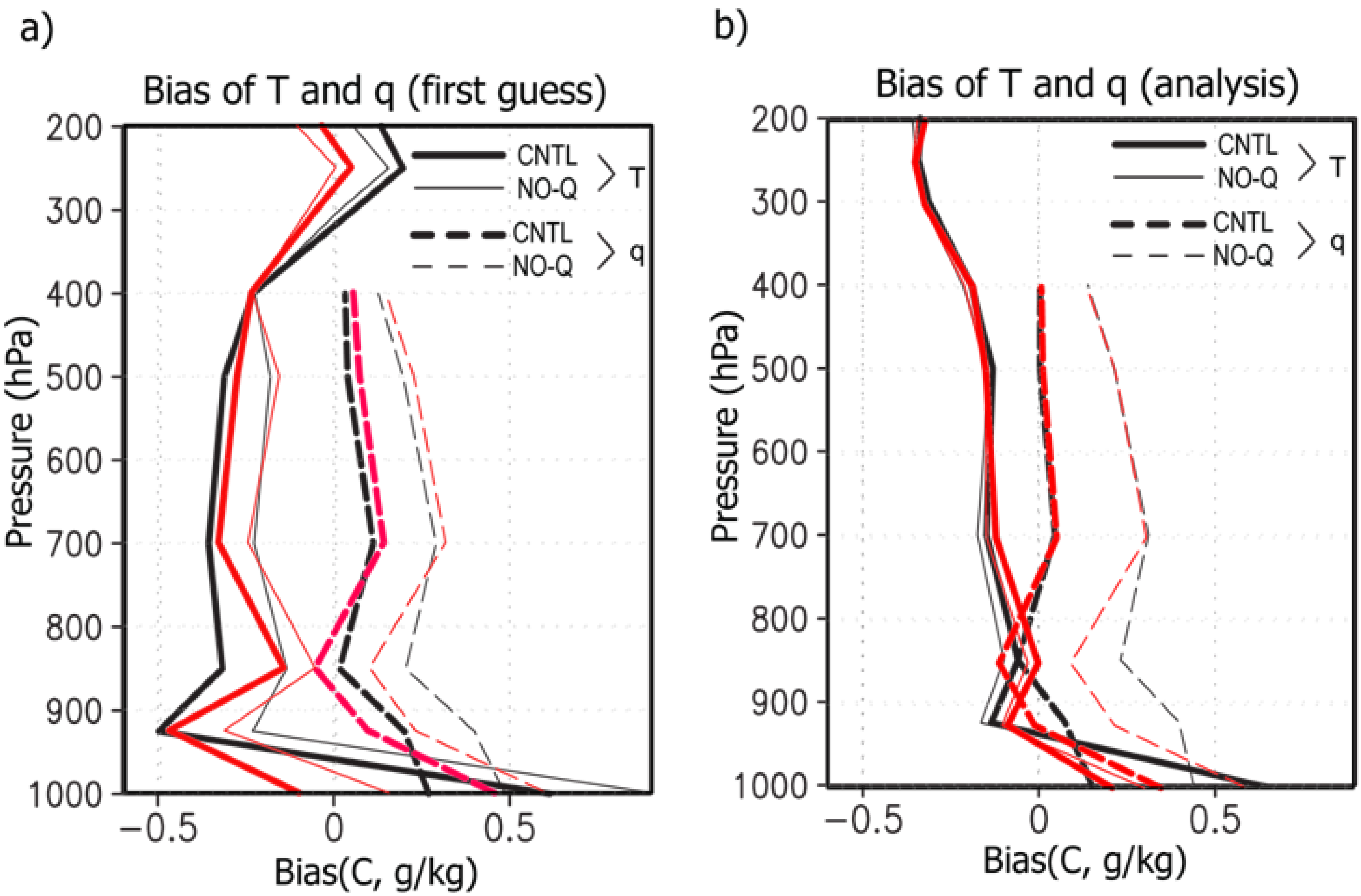
Model versus Data assimilation

Model physics has not been changed, but much in data assimilation

Global model predictability highly depends on initial data quality

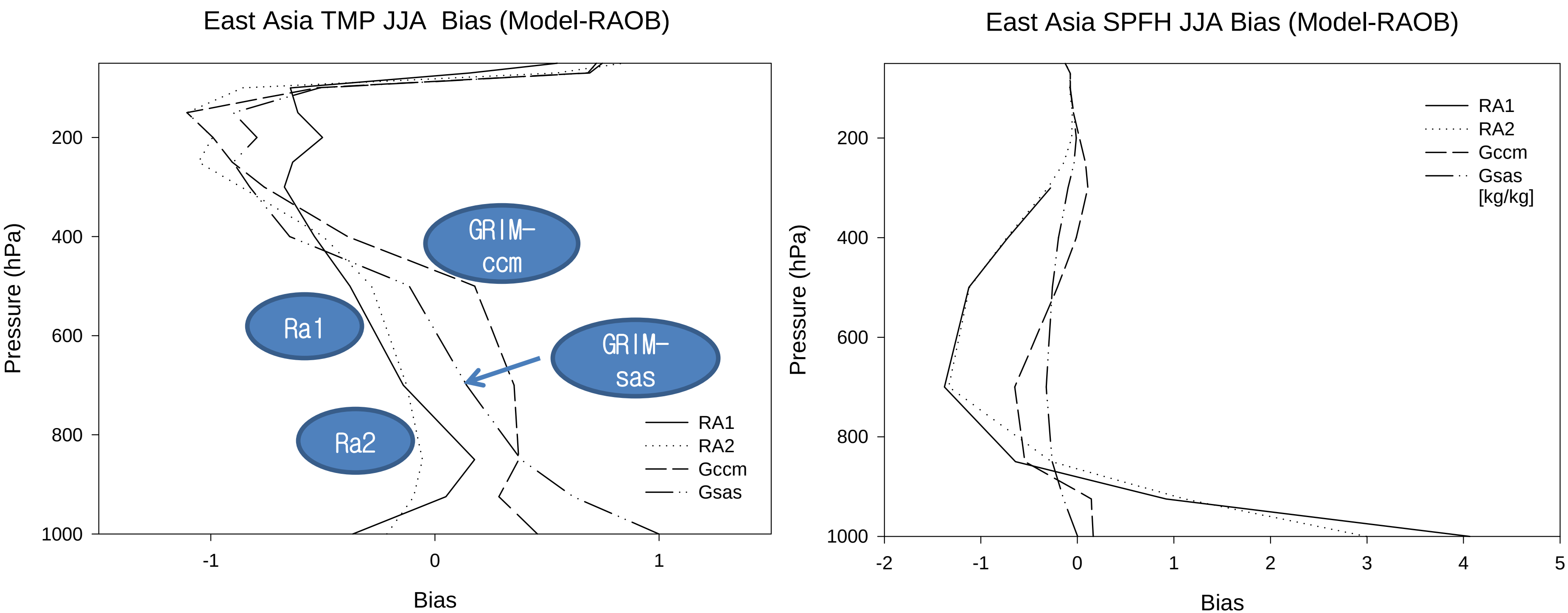
Model is perfect ? or Saturated ? or less important than assimilation ?

If the model is upgraded ? (MRF ➔ YSU)



Moisture effects on assimilated data
Hwang and Hong (2009, ATP)

Model versus Data assimilation



Differences in model physics overwhelms the differences in data assimilation package

The impact of model uncertainties on analyzed data in a global data assimilation system (Hong et al. TAO, in review)

Model versus Data assimilation

Synoptic scale variability highly depends upon the initial condition

Efforts given to model physics and dynamics play an non-trivial role in improving the initial condition

Data → Assimilation → Dynamics → Physics → Forecast

Initial condition → dynamics ┌→ synoptic scale

Model → physics → meso-scale