PBL and precipitation interaction and grey-zone issues

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(Korea Institute of Atmospheric Prediction Systems: KIAPS)

Overview of KIAPS (seminar Nov. 16th, 15:30)

❒ Purpose : Developing a next generation global operational model for KMA

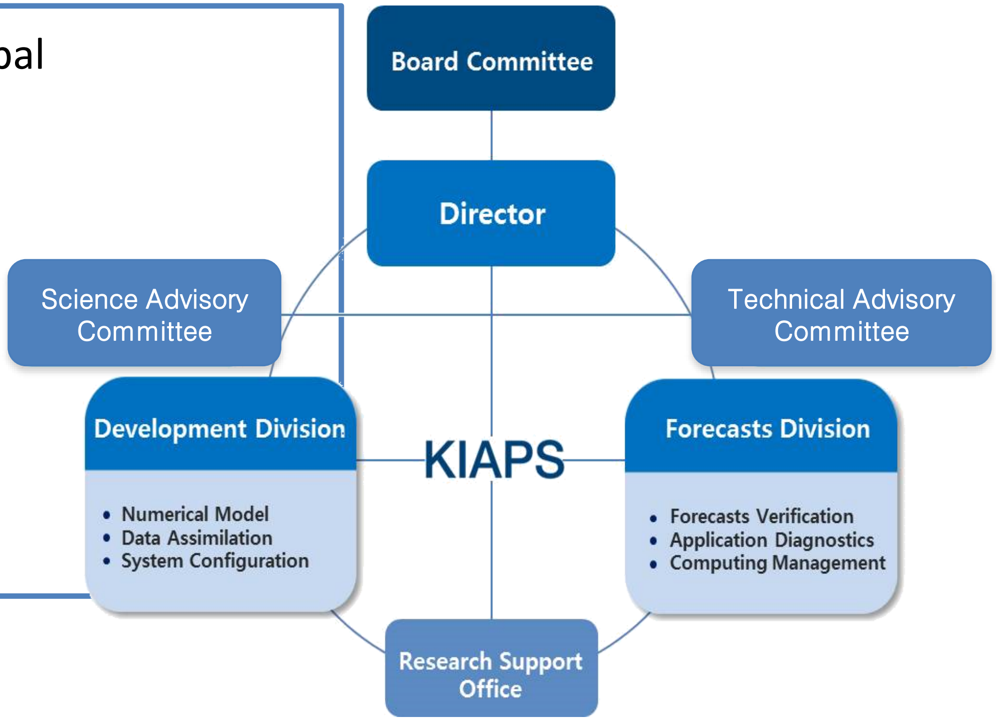
❒ Project period : 2011~2019(total 9 years)

❒ Total Budget: $95 million

2015 budget -$8.5 million

❒ KIAPS is founded at Feb. 15th 2011

- organization: 2divisions, 6teams, 2office
- Man power: 58/58 + 10



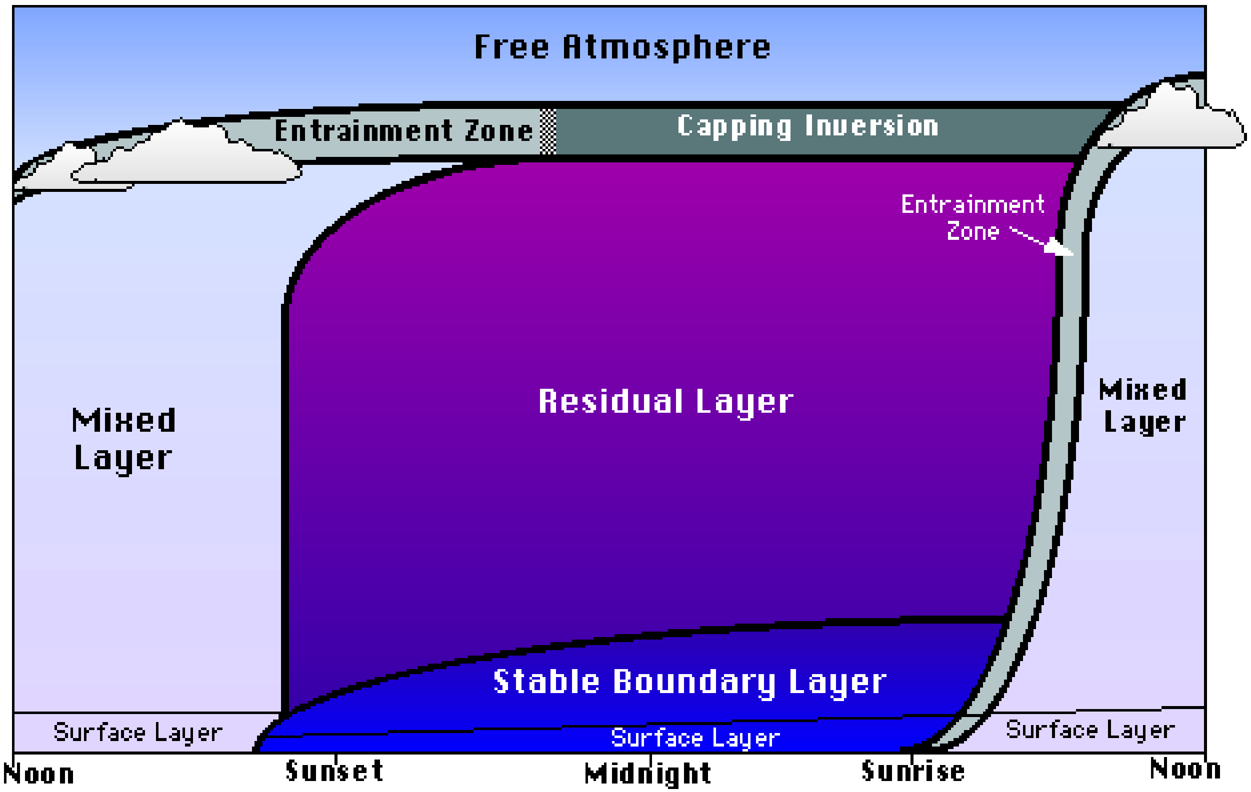
Total	Director	Research Staff				Administrative staff		
		Principal Researcher	Senior Researcher	Researcher	Assistant	Senior Staff	Staff	Assistant
58+10	1	13	26	12	5	3	3	5

Presentation

- ✓ Overviews of PBL parameterizations
- ✓ PBL effects on precipitating convection in MRF model
  (MRF PBL, Hong and Pan, 1996)
- ✓ PBL in cloud-resolving precipitating convection
  (YSU PBL, Hong et al., 2006)
- ✓ A turbulent transport at gray-zone resolutions
  (Shin-Hong PBL, Shin and Hong, 2013, 2015)
- ✓ PBL and precipitation at grey-zone resolutions
  (Preliminary results …..)

Parameterizations : Vertical diffusion (PBL)

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.

Parameterizations : Vertical diffusion (PBL)

Daytime profiles

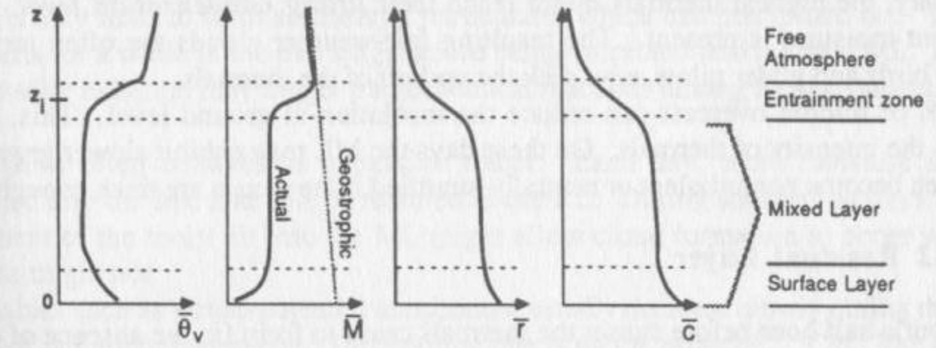


Fig. 1.9 Typical daytime profiles of mean virtual potential temperature $\overline{\theta}_v$, wind speed $\overline{M}$ (where $\overline{M}^2 = \overline{u}^2 + \overline{v}^2$), water vapor mixing ratio $\overline{r}$, and pollutant concentration $\overline{c}$.

Daytime flux profiles

Nighttime flux profiles

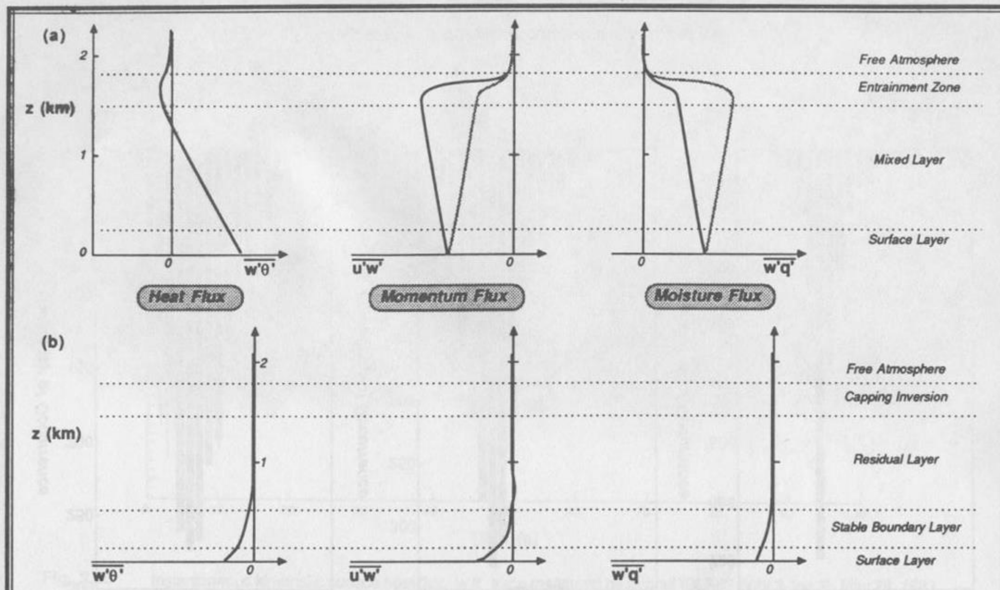
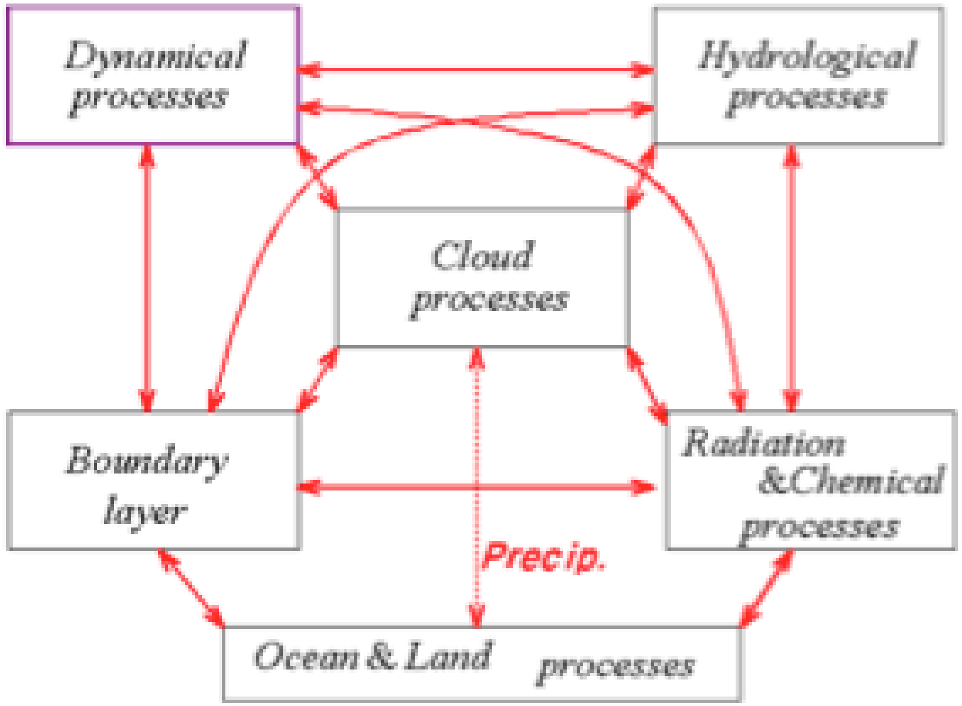


Fig. 2.15 Idealized vertical soundings of turbulent fluxes for the (a) convective mixed layer and (b) stable boundary layer.

Stull (1988)

Parameterizations : 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.

Subgrid scale process & Reynolds averaging…

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

then eq.(1) becomes

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

(first three advection terms: ①; the three turbulent flux terms: ②)

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

* How to parameterize the effect of turbulent transport

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

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

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

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

taking Reynolds averaging,

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

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

Classifications : how to determine, k_c

i) Local diffusion (Louis 1979)

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

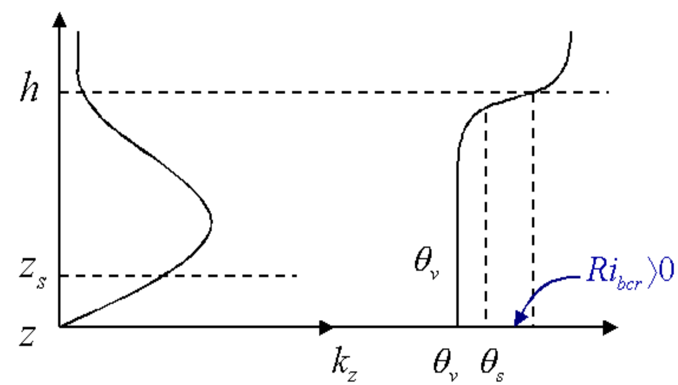
Local Richardson number

ii) Nonlocal diffusion (Troen and Mahrt 1986)

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

small eddies strong updrafts

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



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

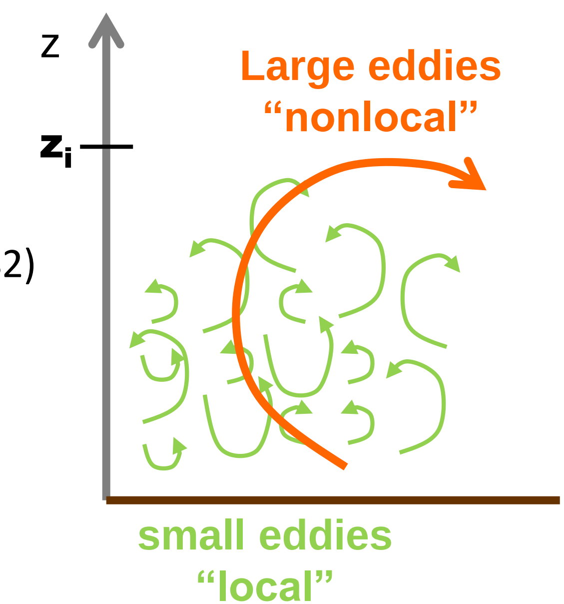
$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial z}(-\overline{wc}) = -\frac{\partial}{\partial z}[-k_c \frac{\partial \overline{c}}{\partial z} + M(c_u - \overline{c})]$$

small eddies strong updrafts

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

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

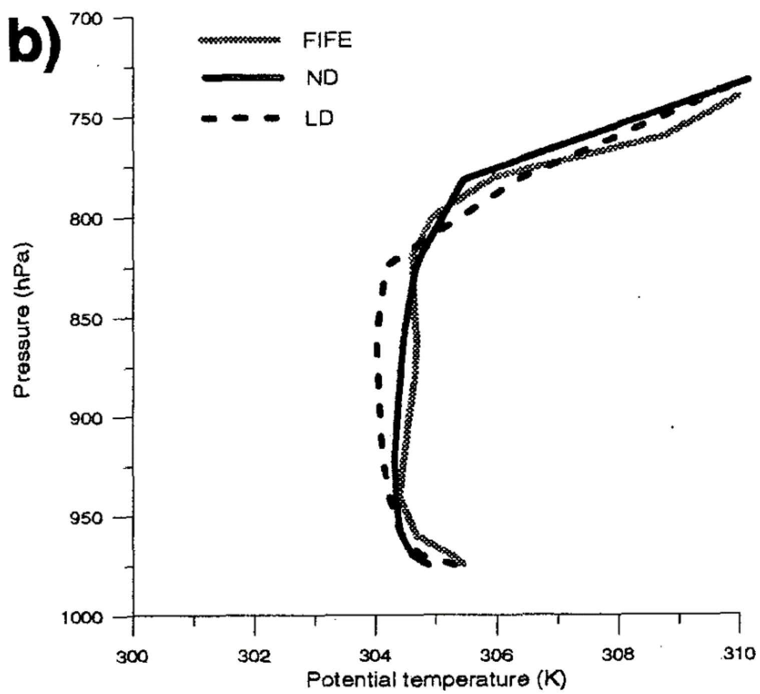
TKE equation : $\overline{u_i u_j} \Longrightarrow k_z = \text{fn (TKE)}$



Local vs. non-local (Hong and Pan 1996)

TABLE 1. Summary of experimental designs.

Experiment	Code	Description	Convection scheme	Vertical diffusion
FIFE 1987	LD	Local diffusion experiment	Updated	Local
	ND	Nonlocal diffusion experiment	Updated	Nonlocal
Heavy-rain case	OPN	Operational physics experiment	Operational	Local
	LD	Local diffusion experiment	Updated	Local
	ND	Nonlocal diffusion experiment	Updated	Nonlocal
Parallel run	MRY	Operational physics experiment	Operational	Local
	MRX	Nonlocal diffusion experiment	Updated	Nonlocal



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

Local scheme (LD) typically produces cololer and moister PBL than nonlocal (ND)

Local vs. non-local : Heavy rain case

Day 1

Day 2

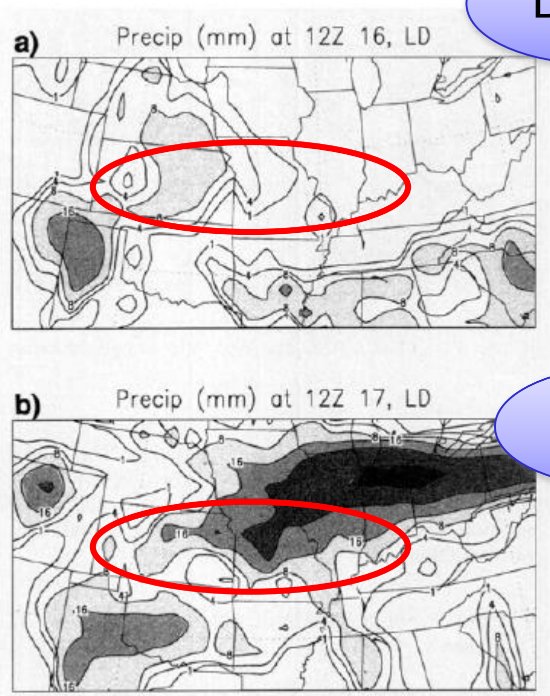


FIG. 9. As in Fig. 7 but for the local diffusion experiment, which utilizes the improved convection scheme.

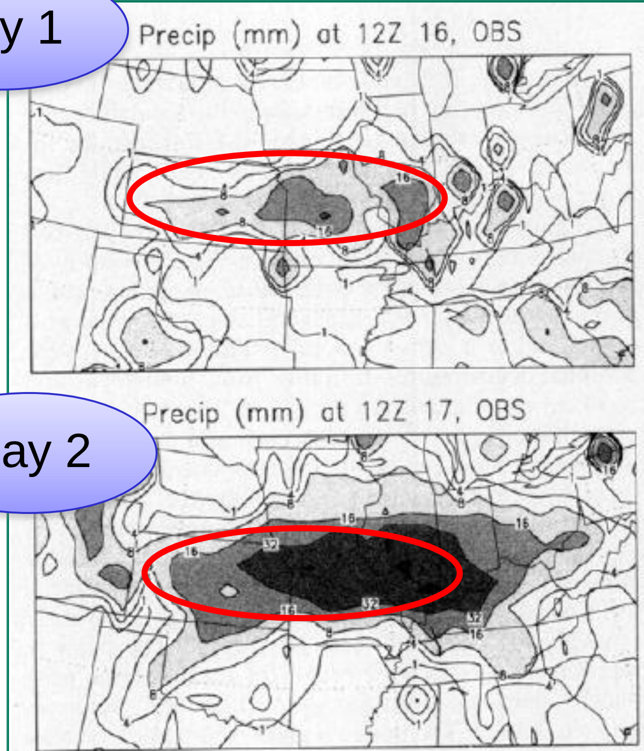


FIG. 7. The analyzed 24-h accumulated rainfall (mm) ending at (a) 1200 UTC 16 May and (b) 1200 UTC 17 May 1995. Areas of rainfall over 8 mm are shaded. Values are box averages on the T126 spectral grid from station data.

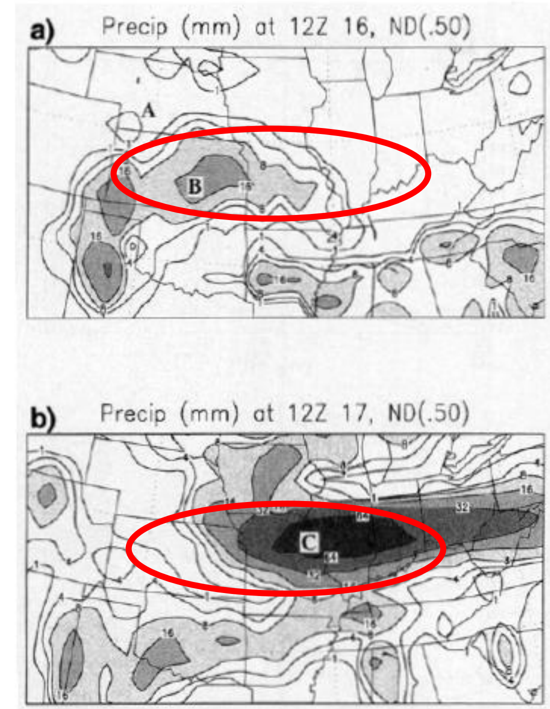


FIG. 10. As in Fig. 7 but for the control nonlocal diffusion experiment with Rib_{cr} = 0.50. Points *A*, *B*, and *C* designate the station points for time–height cross-sectional analyses in Figs. 11 and 13.

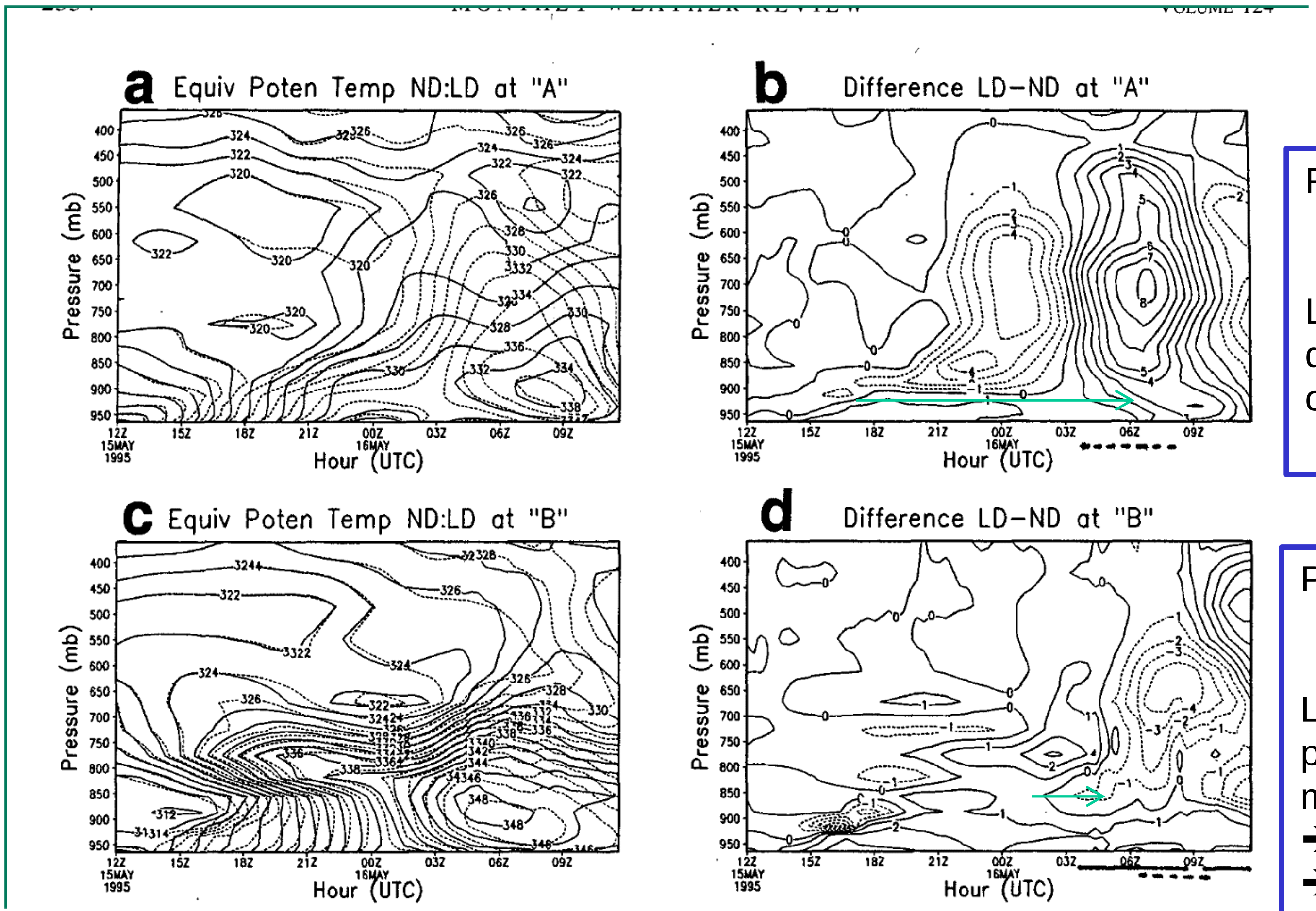
LD

OBS

ND

Shaded is the heavy rain area

Local vs. non-local : Heavy rain case



PBL is shallow : light
precipitation in LD

LD PBL is shallower (moist) in daytime, producing convective overturning in early evening

PBL is deep : heavy
precipitation in ND

LCL is high and convection parcel originates above the mixed layer (850 hPa)

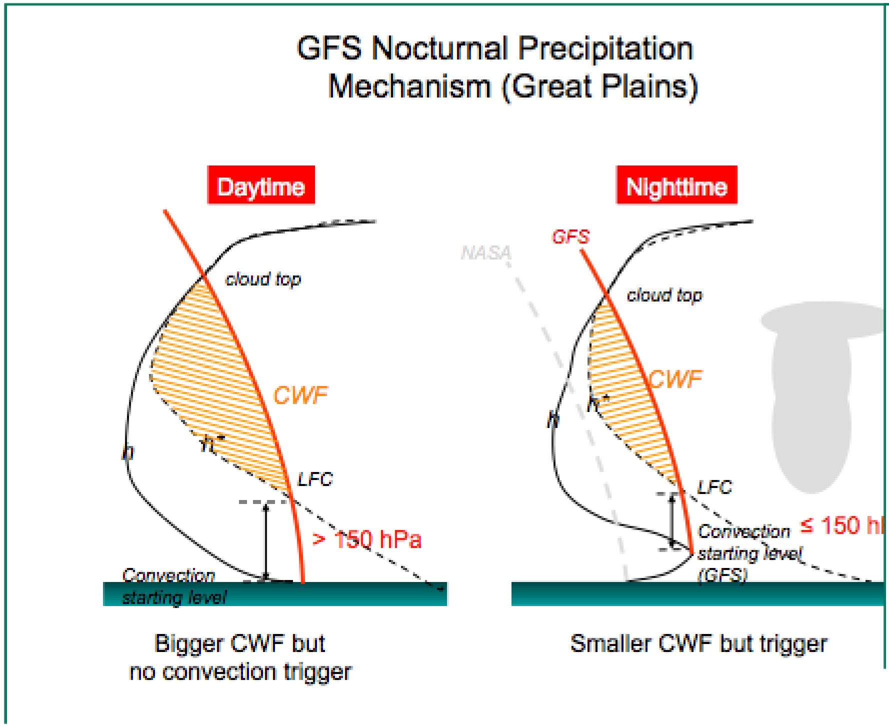
➔ PBL top is moister in ND

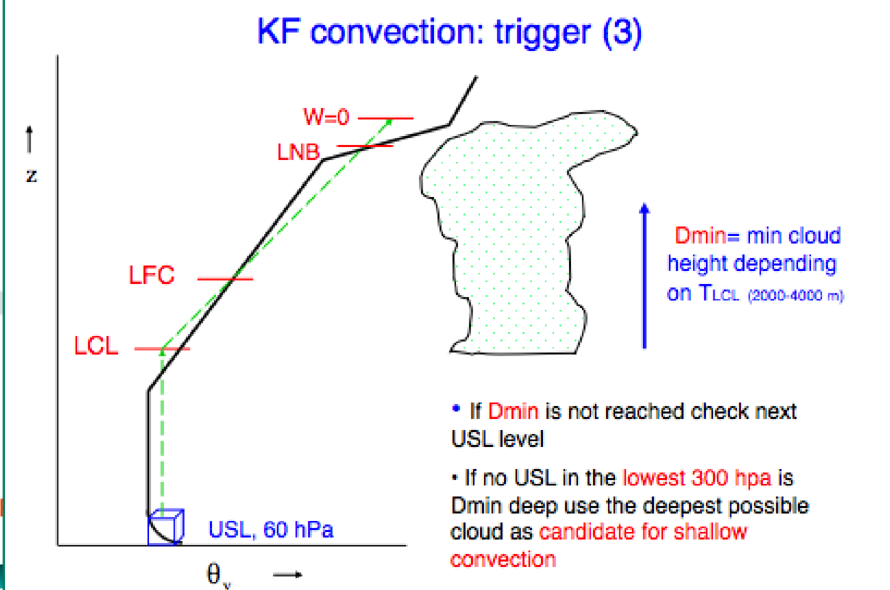
➔ ND produces vigorous nighttime convection

Local vs. non-local : Concept

In contrast to the dry case, the resulting rainfall is significantly affected by the critical Ri, which is due to the fact that the simulated precipitation is more sensitive to the boundary layer structure when the PBL collapses than when it develops.

PBL mixing in daytime determines the CIN for daytime convection, also determines the trigger for nighttime overturning (residual effect of daytime mixing)





PBL and cloud-resolving convection

(Hong et al. 2006, YSU PBL)

$$-\overline{w'\theta'} = K_h\left(\frac{\partial\theta}{\partial z}-\gamma_h\right)-\overline{w'\theta'}_h\left(\frac{z}{h}\right)^3$$

PBL and cloud-resolving convection

Model setup : BAMEX 2002

- Cold front (10-11 Nov 2002)
- 4 km grid (cloud-resolving)
- YSU PBL compared to MRF PBL
- WSM6 microphysics
- NOAH land surface
- No cumulus parameterization scheme

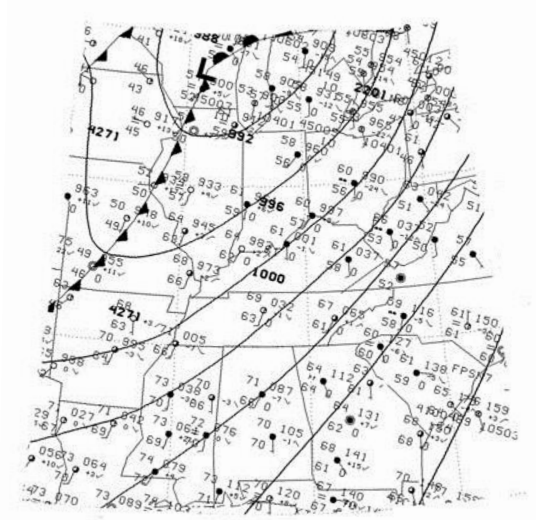
Initial time : 12Z 10 November 2002

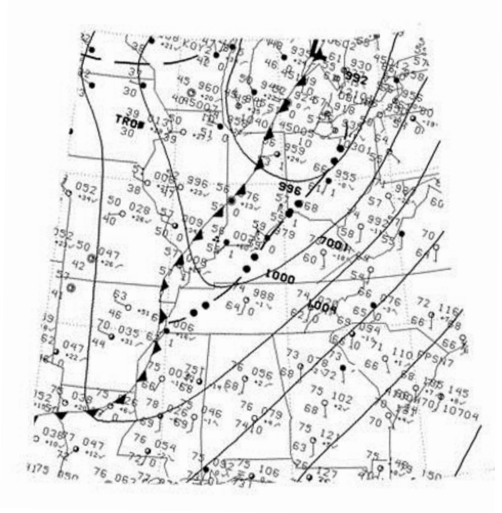
Initial and boundary data : EDAS analyses

Focus : Precipitation response due to the differences
in YSU and MRF PBL

PBL and cloud-resolving convection

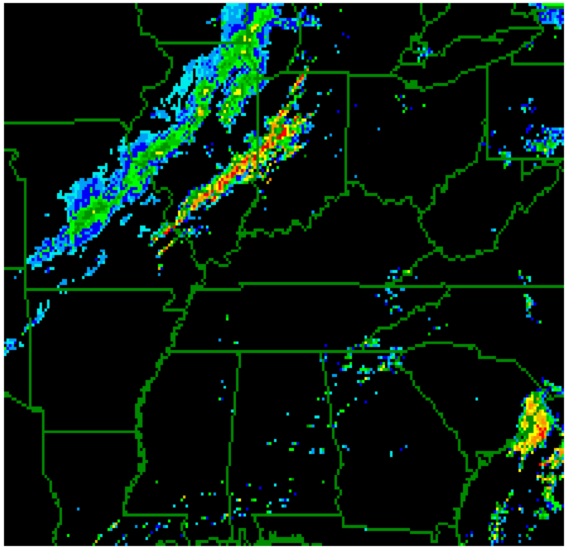
12Z 10 November **00Z 11 November 2002**

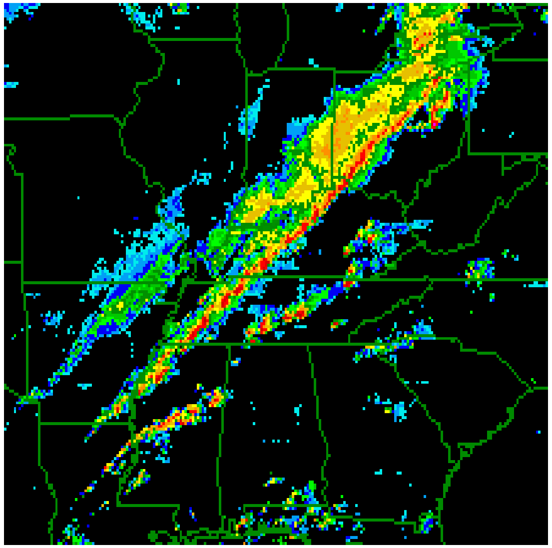




BAMEX (Bow-Echoand Mesoscale convective Vortex Experiment, Davis et al. 2004)

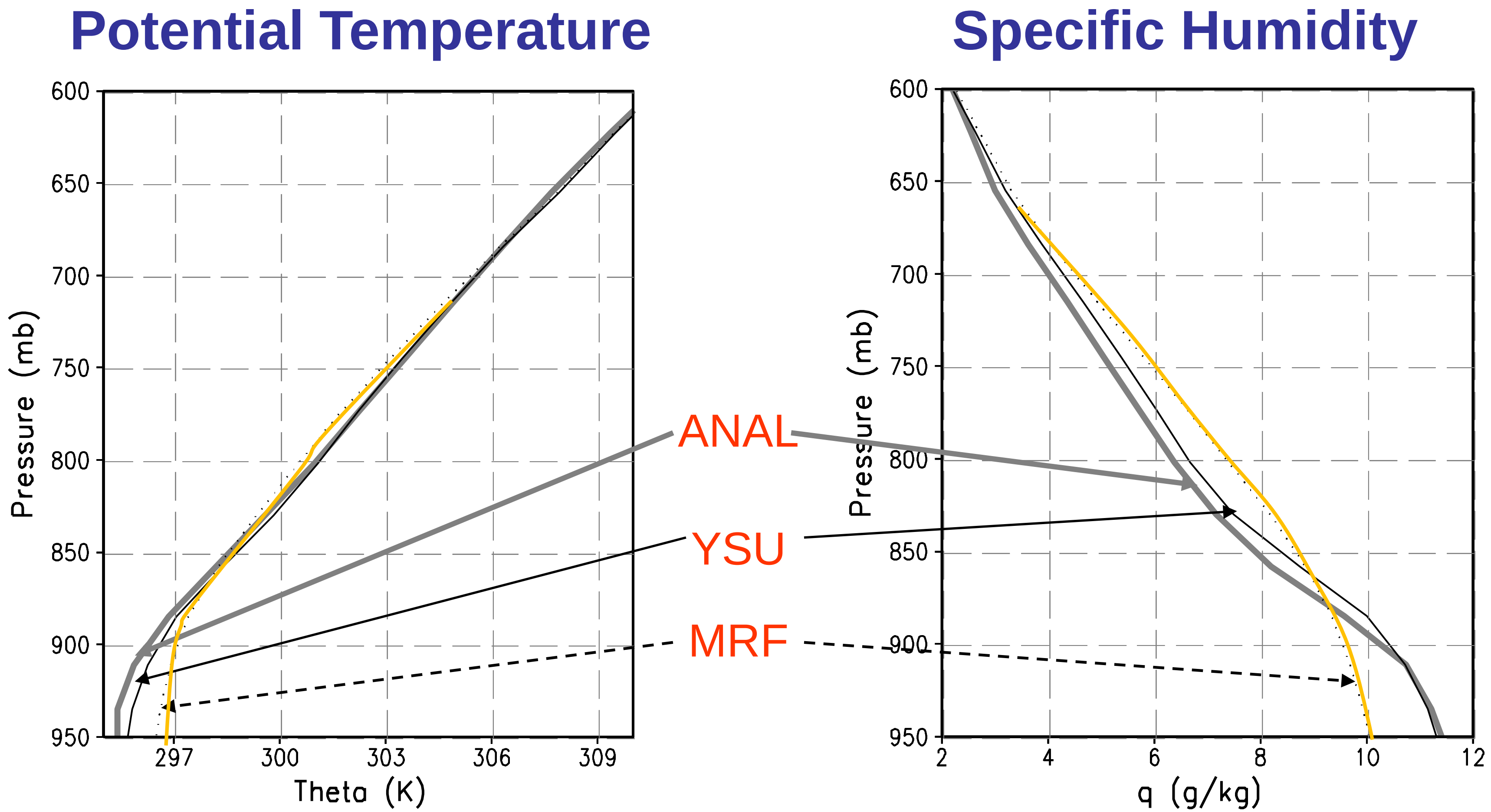
18Z 10 (noon) November **00Z 11 (evening)**





75 tornados in 13 states on the night of Nov. 10th, 2002

PBL and cloud-resolving convection



- The PBL with the YSUPBL is cooler and moister below 870 mb, whereas impact is reversed above → closer to the observed
- Impact is more significant for moisture than temperature

Dry convection is easy to explain, but
How can we explain the differences in precipitation ?

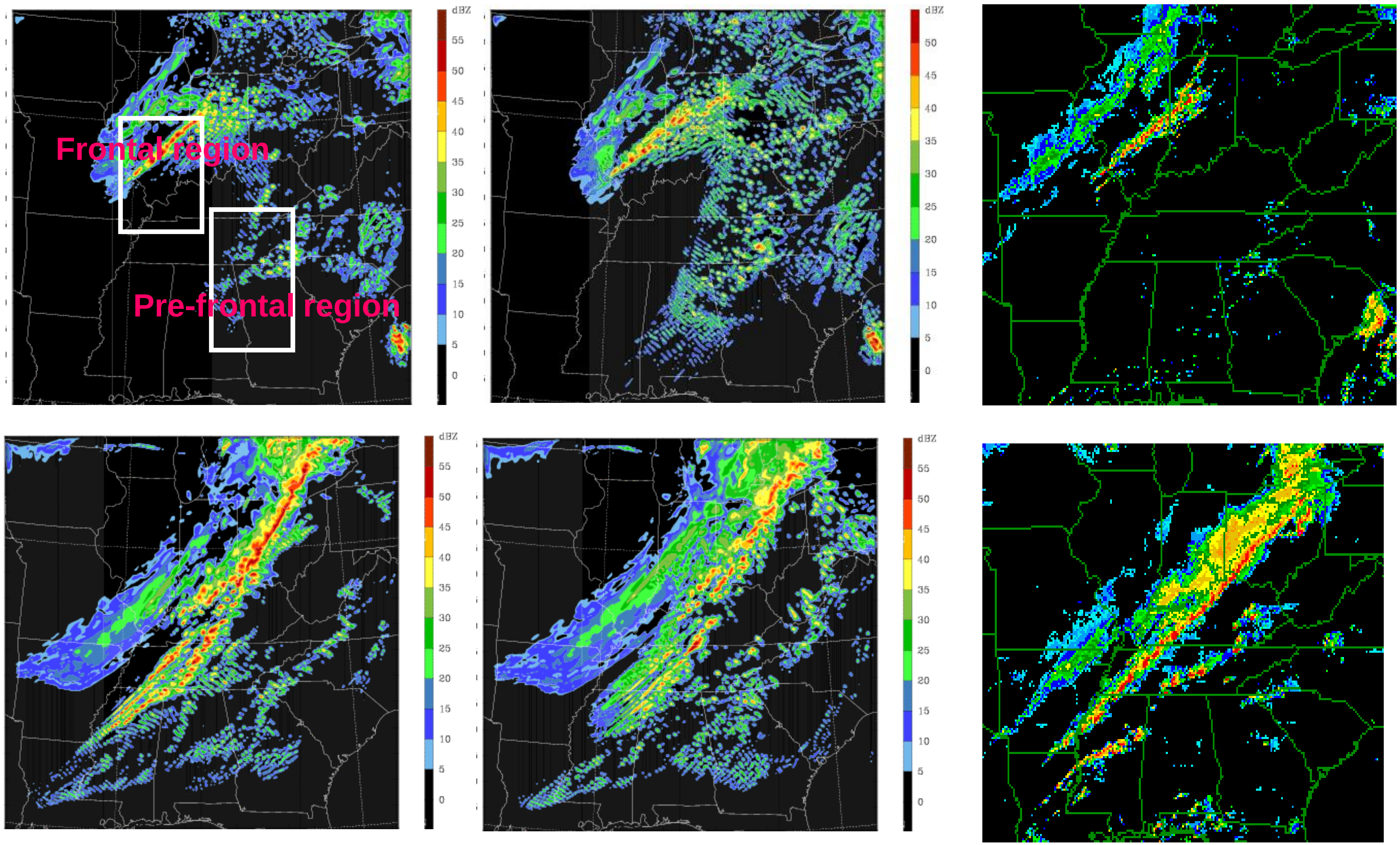
PBL and cloud-resolving convection

Maximum radar reflectivity (dBz)

YSU MRF OBS

18Z 10 Noon

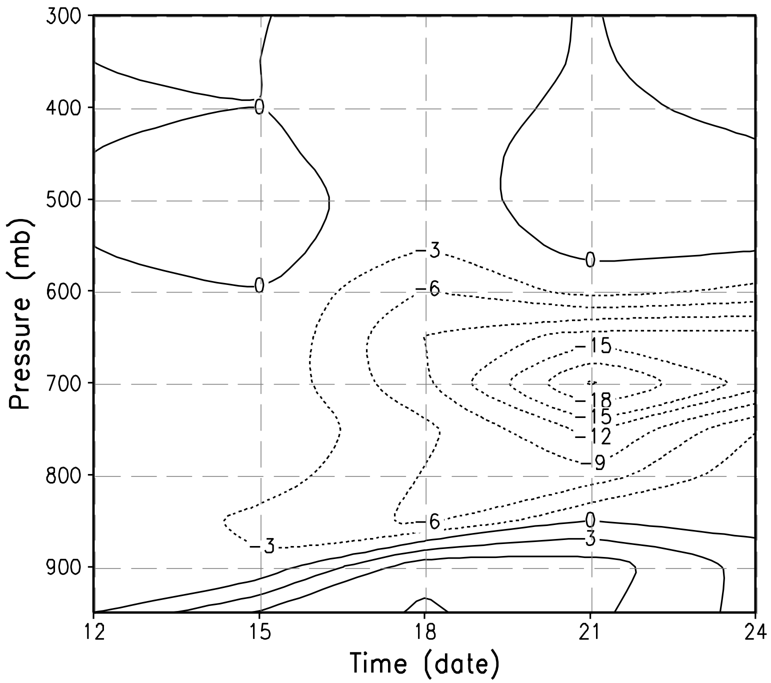
00Z 11 Evening



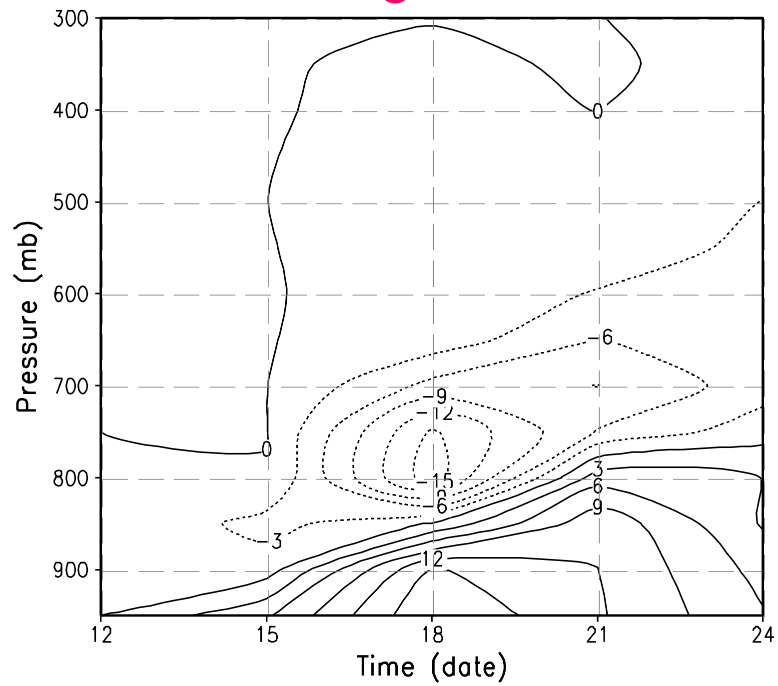
PBL and cloud-resolving convection

Time series of domain-averaged relative humidity (YSU-MRF)

Pre-frontal region



Frontal region



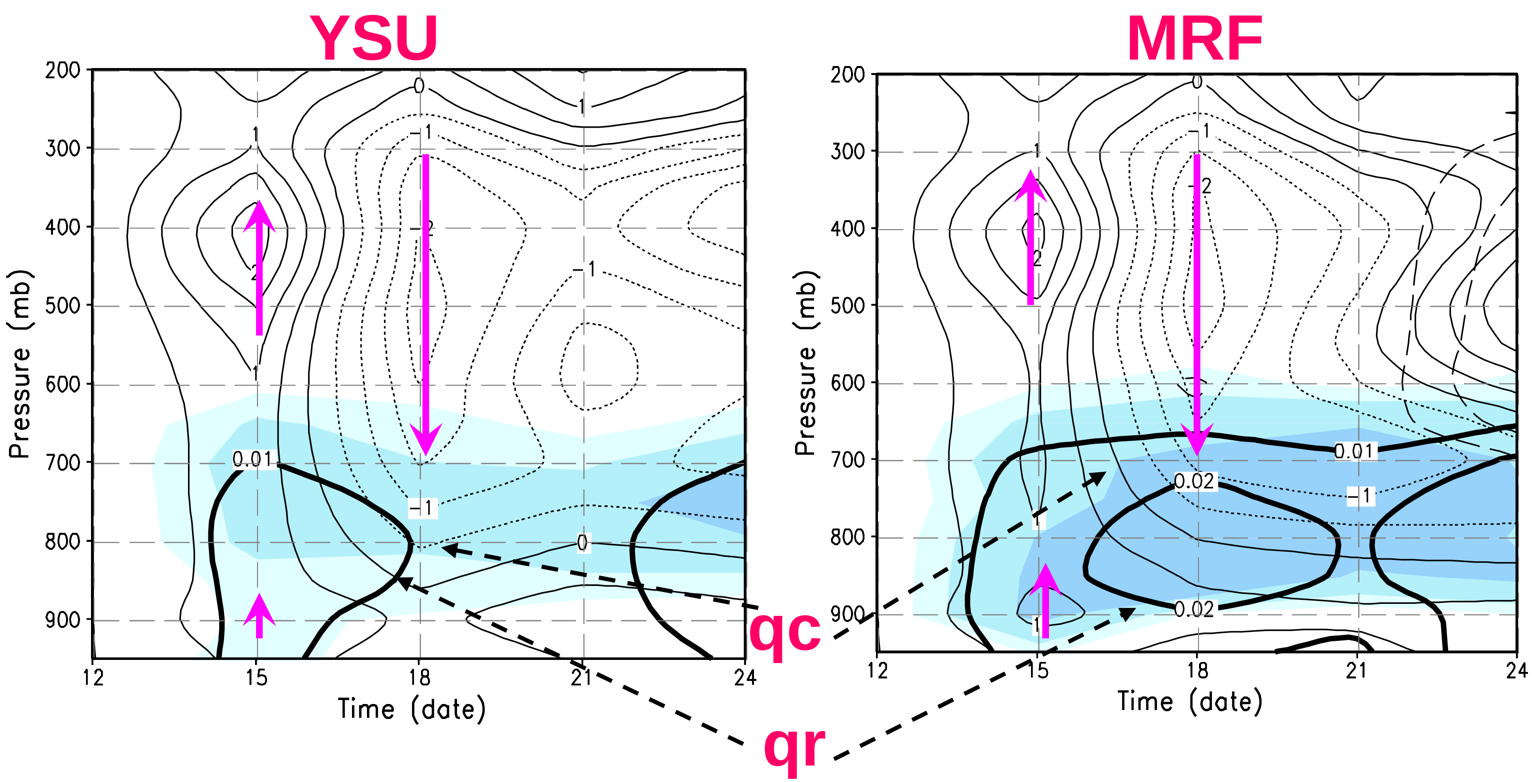
- Moistening within the PBL and drying above due to weaker mixing by the YSUPBL than the MRF

- Temperature differences are opposite signs

Should explain the precip difference

PBL and cloud-resolving convection

Time series of w, qc, and qr in the pre-frontal region

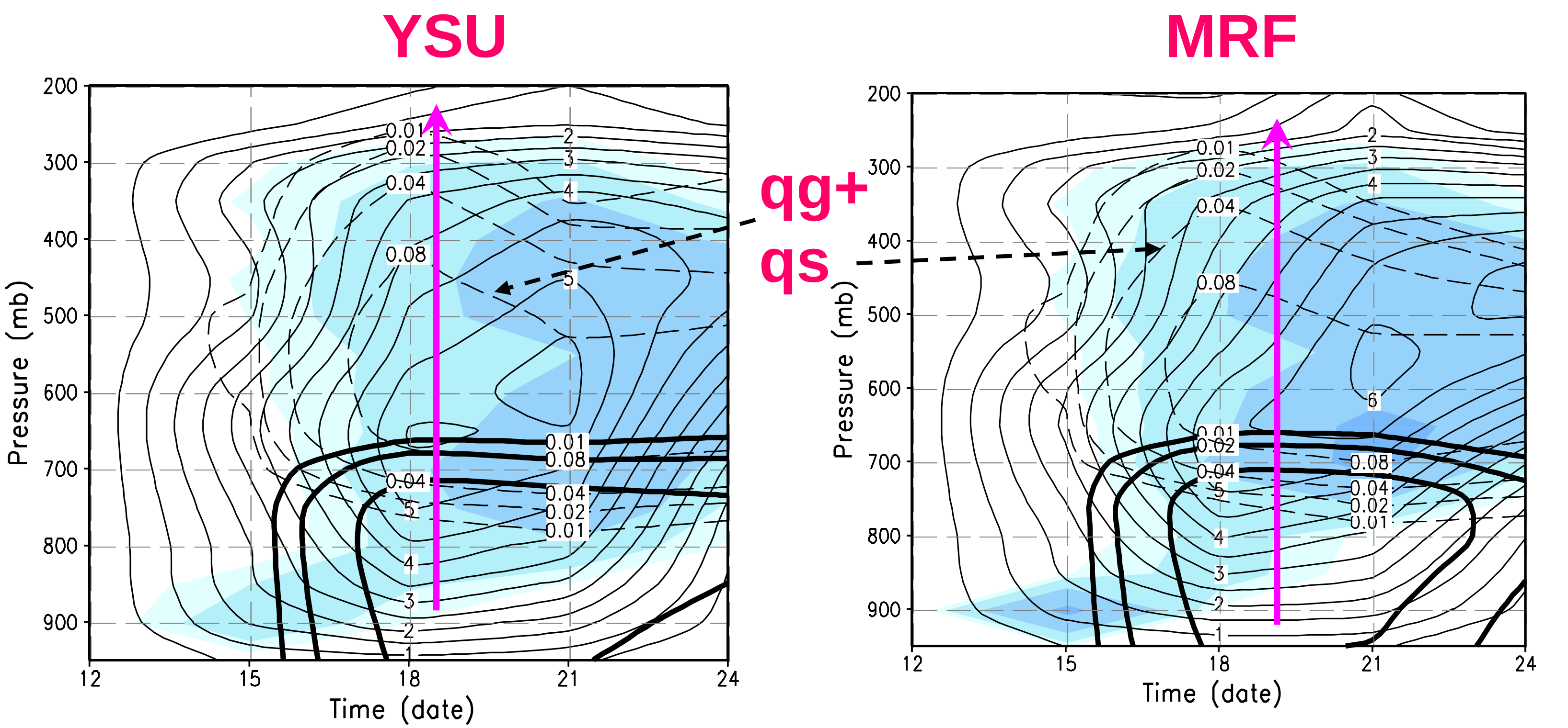


•Compared to the MRF, YSU PBL induces a less mixing within PBL due to a stronger inversion → less clouds formation below 600 mb despite a larger CAPE → less rain water formation → less precipitation at the surface

•Precipitation is organized by thermal forcing and clouds are shallow

PBL and cloud-resolving convection

Time series of w, qc, qr, and qg in the frontal region



•Same scenario to the pre-frontal region in terms of PBL structure, but different impact on precipitation due to different synoptic situation
→ Intense precipitation after 21Z due to less evaporation of falling rain drops in moister PBL with YSU PBL

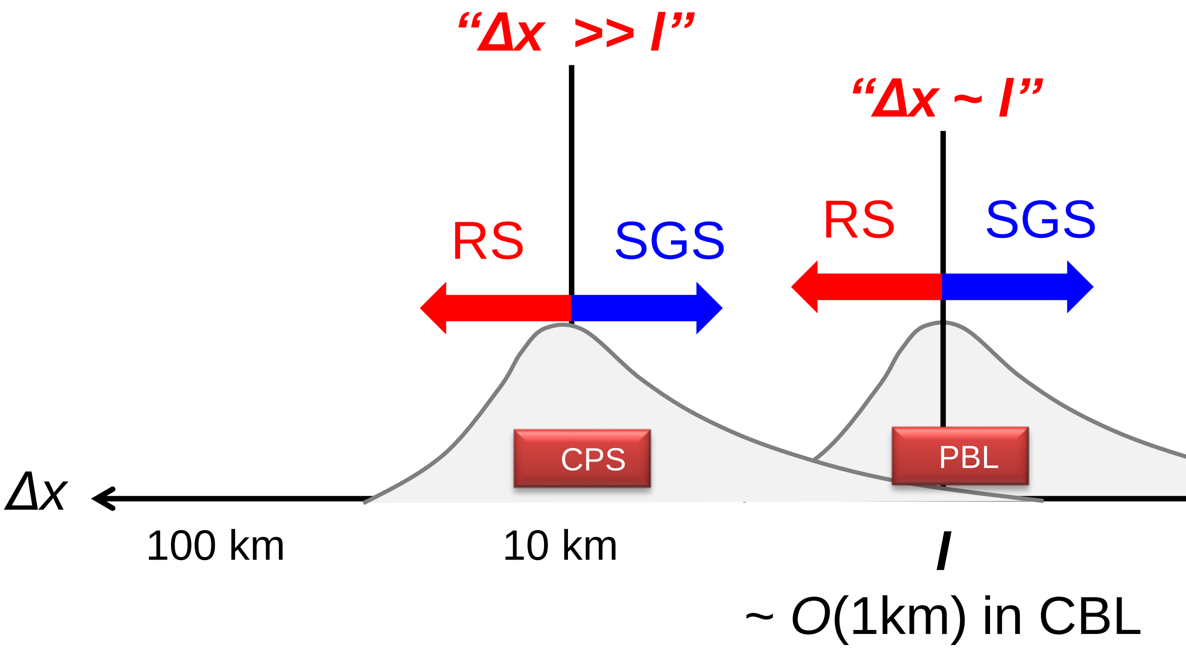
•Precipitation is organized by strong dynamical forcing and clouds are deep

PBL and cloud-resolving convection

Impact of PBL on precipitation processes is intimately related to not only the onset of convection, but also the type of convection

(shallow vs. deep ; local vs. synoptic forcing)

At forthcoming high resolutions : PBL gray-zone



In the gray zone:

the process is *partly resolved*.

Operational NWP/GCM → **within 5 years**

Hong and Dudhia (2012)

(Hydrostatic → Non-hydrostatic)

Mesoscale simulations in research communities

CRM → **Bryan et al. (2003)**

Gray-zone PBL: Concepts & Methods

- **Shin, H. H., and S.-Y. Hong, 2013**: Analysis on Resolved and Parameterized Vertical Transports in Convective Boundary Layers at Gray-Zone Resolutions. ***J. Atmos. Sci.***, doi:10.1175/JAS-D-12-0290.1.

- **Shin, H. H., and S.-Y. Hong, 2015**: Representation of the Subgrid-Scal e Turbulent Transport in Convective Boundary Layers at Gray-Zone Resolutions**. Mon. Wea. Rev.**

Methods

(1) Construction of the **'true'** data for **50–4000 m Δ**

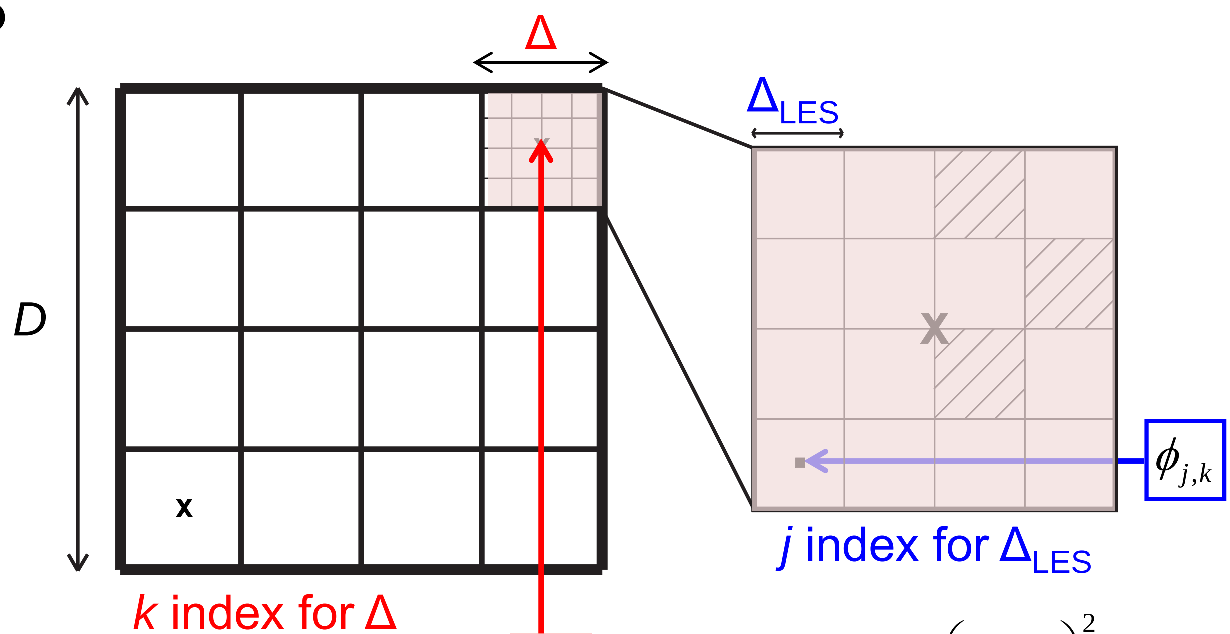
D (=8000 m ~ Δ_{1DPBL}) *Domain size* ⇐ **50–4000 m Δ *Reference data* (includes gray zone)** ⇐ Δ_{LES} (=25 m) *Benchmark LES*

For a variable φ

$$< \phi > = (JK)^{-1} \sum_{j,k} \phi_{j,k}$$

$$= K^{-1} \sum_{k} \overline{\phi}^{\Delta_k}$$

$$K = \left(\frac{D}{\Delta}\right)^2$$

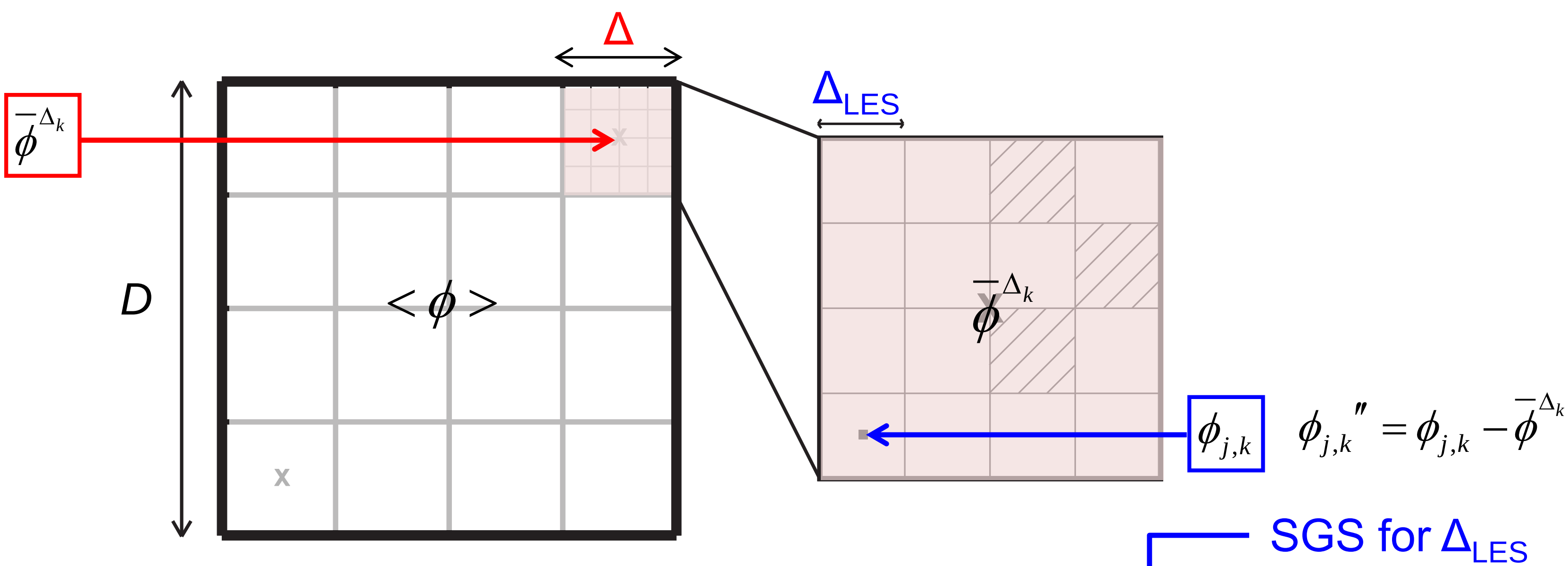


$$\overline{\phi}^{\Delta_k} = (J)^{-1} \sum_{j} \phi_{j,k} \quad J = \left(\frac{\Delta}{\Delta_{LES}}\right)^2$$

Methods

(2) Construction of the 'true' data for 50-4000 Δ

Turbulent vertical transport over the whole domain, **for Δ**



$$\langle w'\phi'\rangle = K^{-1}\sum_k\left(\overline{w}^{\Delta_k}-\langle w\rangle\right)\left(\overline{\phi}^{\Delta_k}-\langle\phi\rangle\right)+K^{-1}\sum_k\left[J^{-1}\sum_j\left(w''_{j,k}\phi''_{j,k}+f^{w\phi}_{j,k}\right)\right]$$

$$= K^{-1}\sum_k\left(\overline{w}^{\Delta_k}-\langle w\rangle\right)\left(\overline{\phi}^{\Delta_k}-\langle\phi\rangle\right)+K^{-1}\sum_k\left(\overline{w''\phi''}^{\Delta_k}+\overline{f^{w\phi}}^{\Delta_k}\right)$$

$$= \langle w'\phi'\rangle^{R(\Delta)} + \langle w'\phi'\rangle^{S(\Delta)}$$

Resolved for Δ **SGS for Δ**

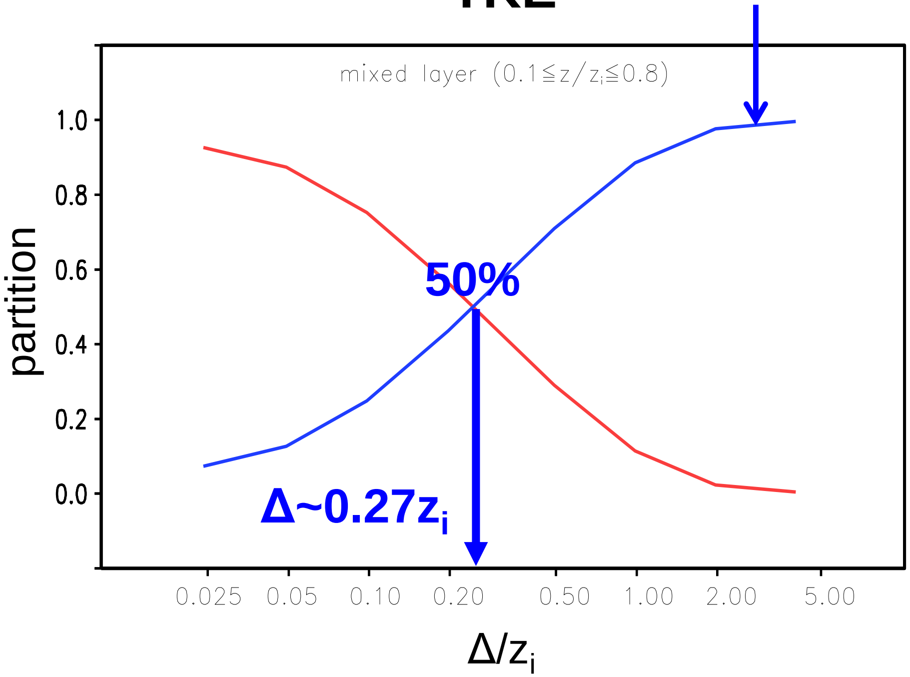
Dorrestijn et al. (2013)
Honnert et al. (2011)
Cheng et al. (2010)

Resolution dependency

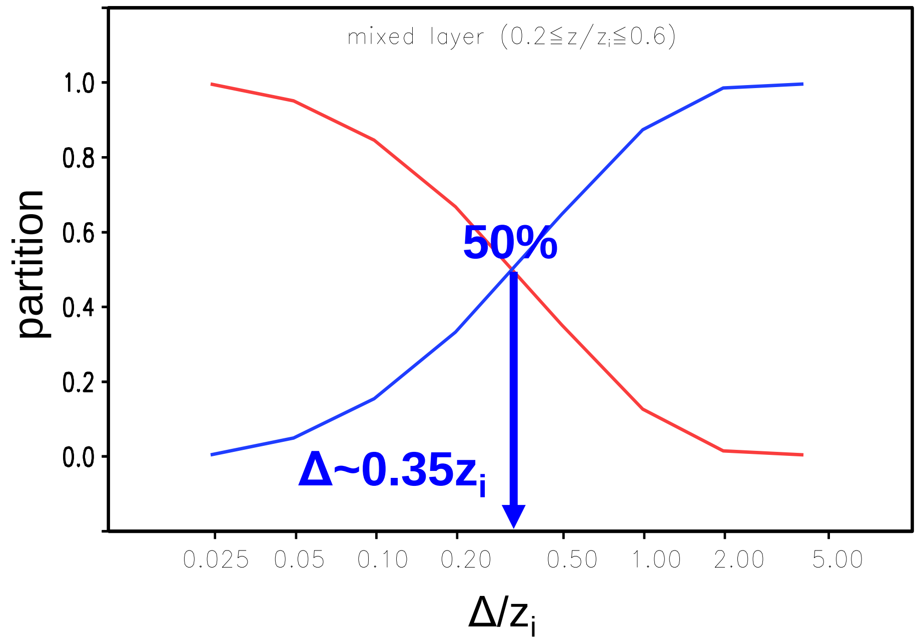
In mixed layer

TKE

to be parameterized



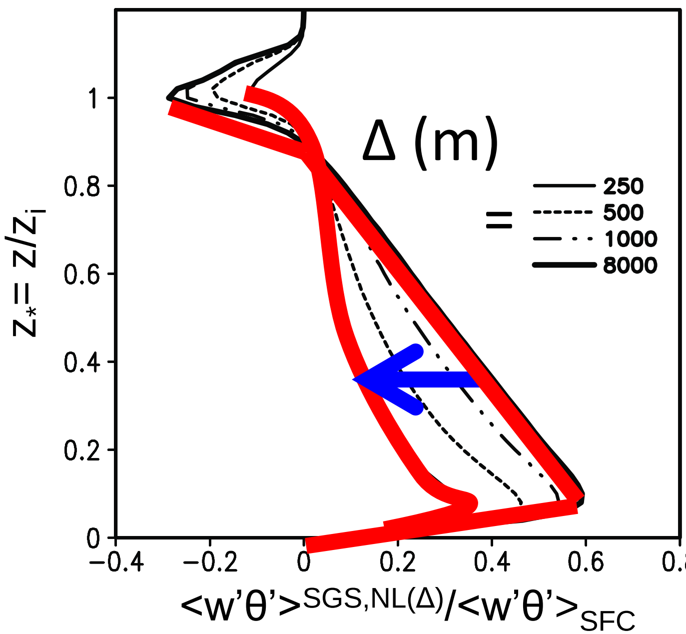
<w'θ'>



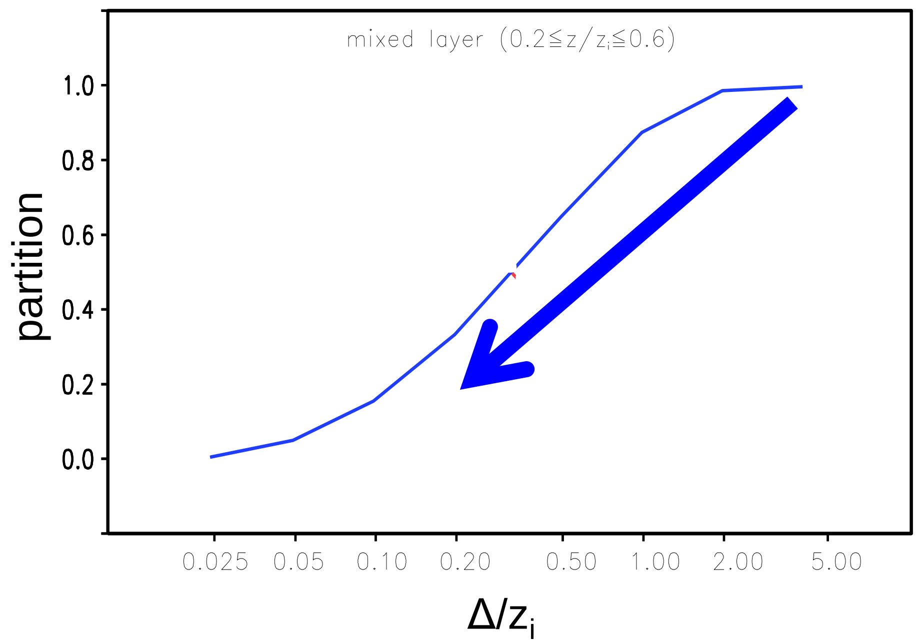
SGS <w'θ'> is 50%–90%: Δ is 360 m – 1230 m

From the Reference data (nonlocal term)

SGS NL transport profile



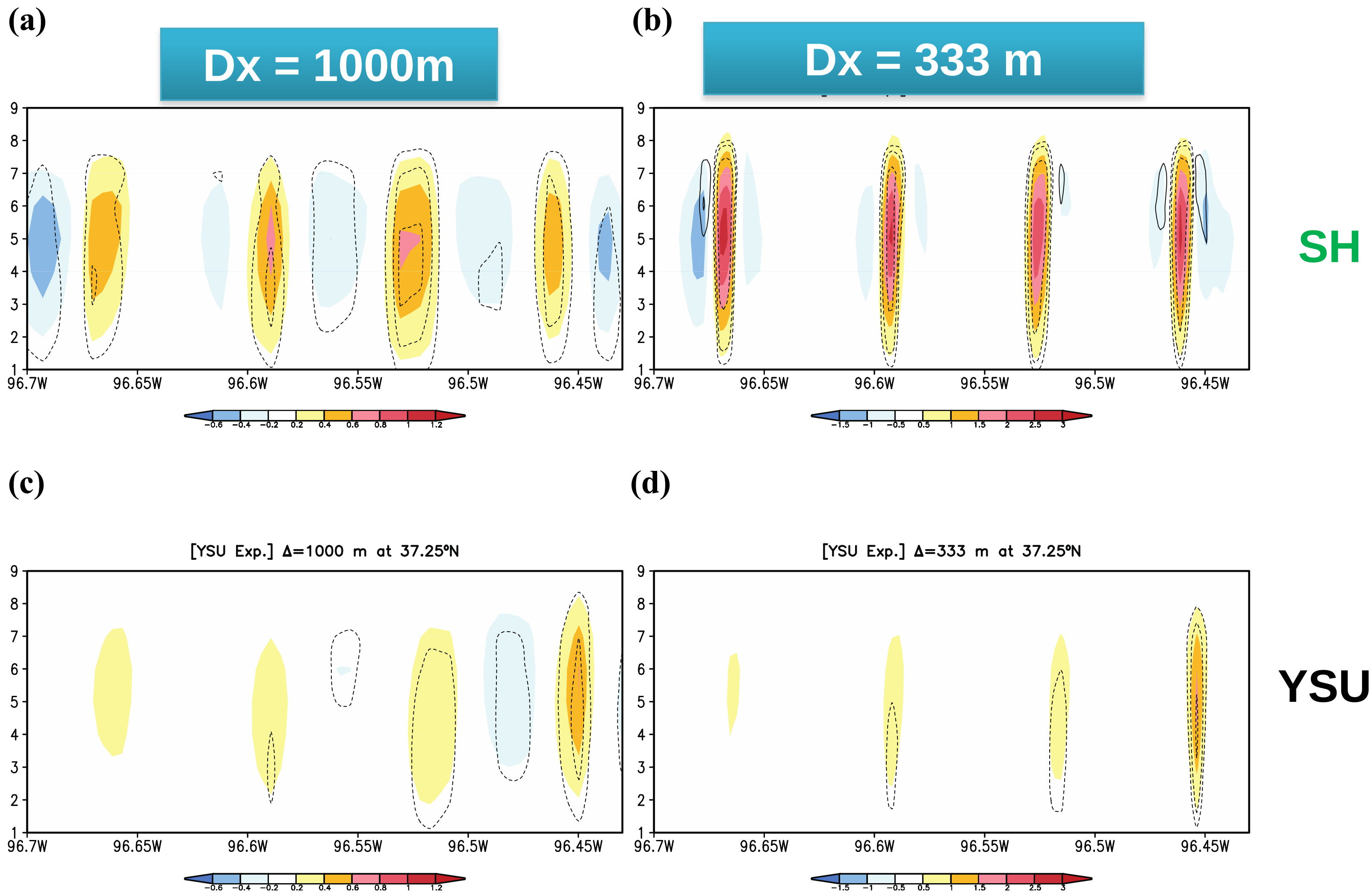
Resolution dependency of SGS NL transport



- ✓ The role of SGS NL transport: **SL cooling**, **ML heating**, **entrainment**.
- ✓ The physical role is **kept for different Δ**.

3D real case experiments : IHOP2002

- *w* (shaded) and *v’w’* (contour) : y-time cross-section

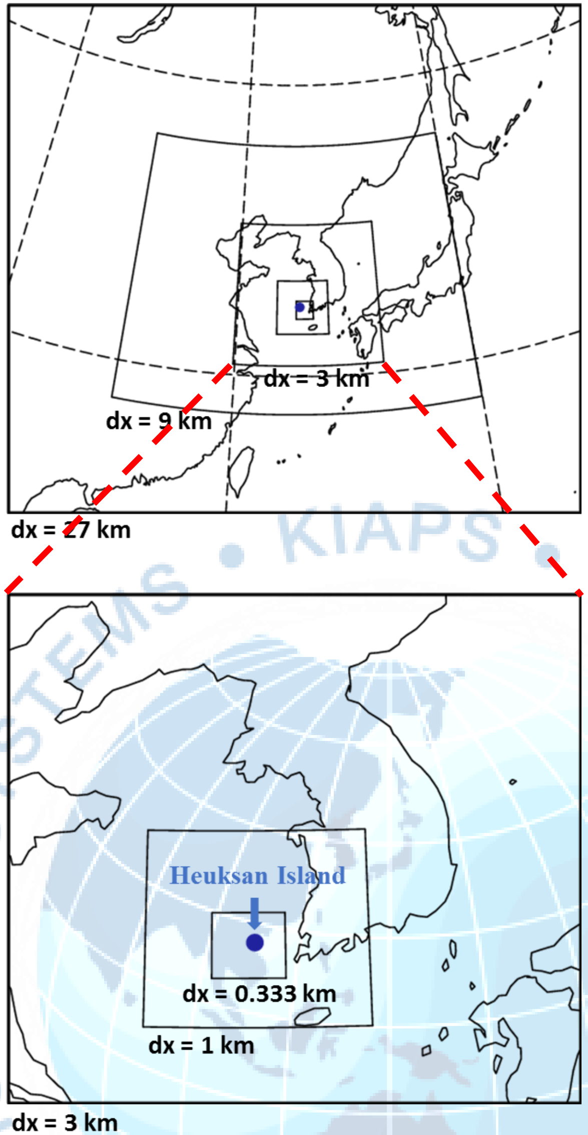


PBL and precipitation at grey-zone resolutions

(YSU PBL vs. Shin-Hong PBL)

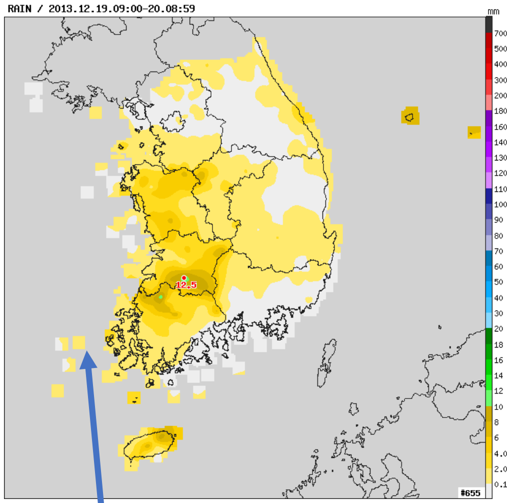
Experimental Design

Model	WRF v3.7.1	
Horizontal resolution	27-9-**3-1-0.333 km** (1-way nesting)	
Vertical resolution	L51 (top: ~50 hPa)	
Time integration	**48-h (00 UTC 18-20 December 2013)**	
Initial & boundary conditions	FNL analysis (1° x 1°, 26 levels with top ~ 10 hPa) NCEP SST analysis (0.5° x 0.5°)	
Diffusion	2nd order vertical diffusion with constant coefficient, 2D Smagorinsky horizontal diffusion	
Physics	Convection	GSAS (scale aware, Kwon and Hong)
	Microphysics	WSM5
	Radiation	RRTMG SW & LW
	PBL	**YSU** (Hong et al. 2006) **SH** (Shin and Hong 2015)
	Land surface	Noah



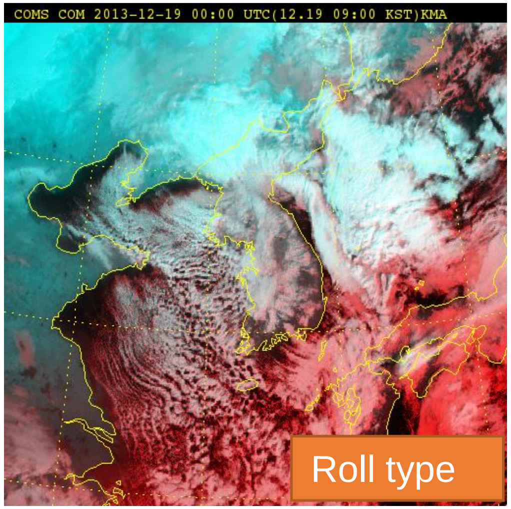
Case overview

2013.12.19-20 00 UTC

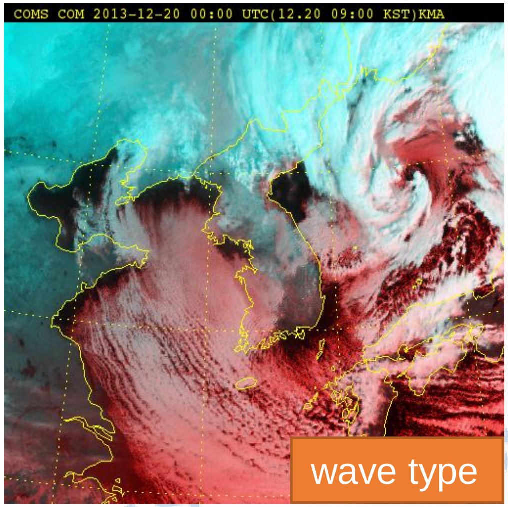


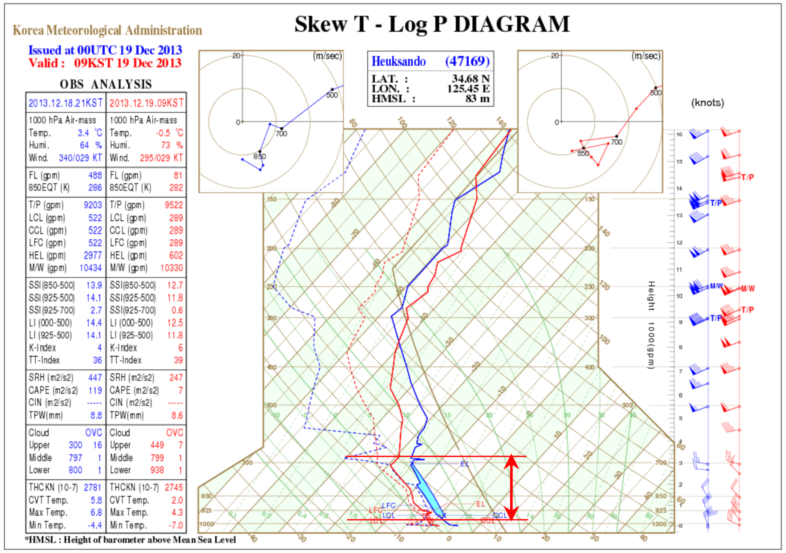
Heuksan Island

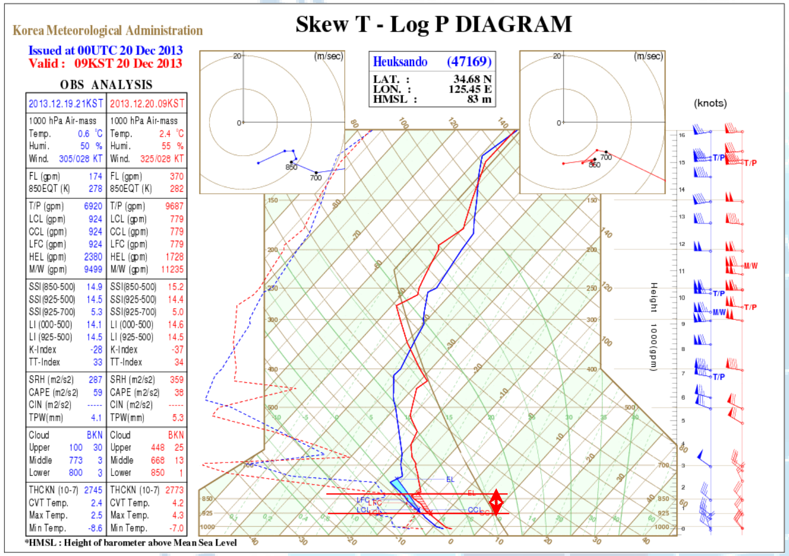
2013.12.19 00 UTC



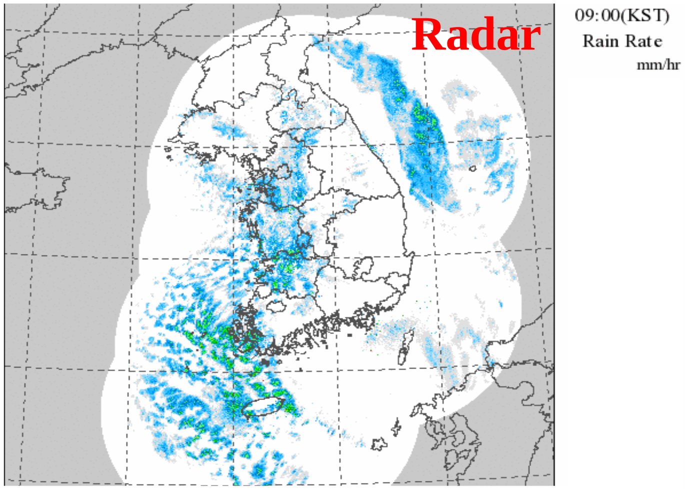
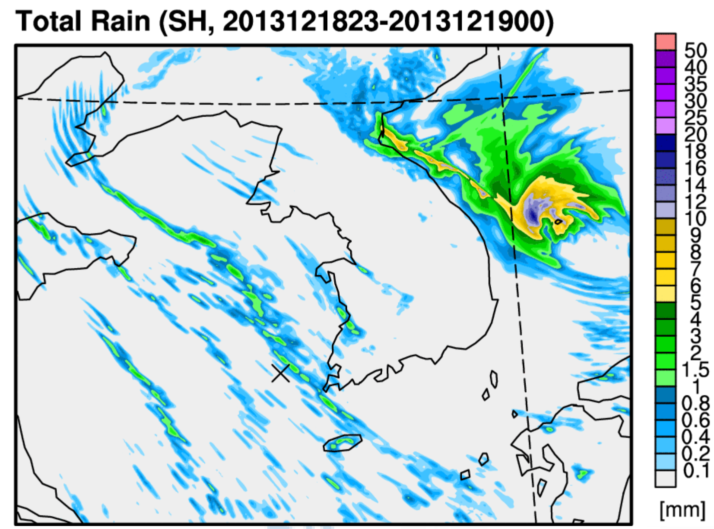
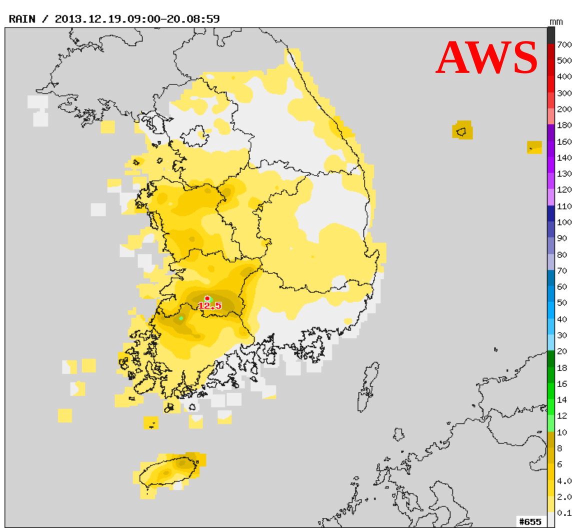
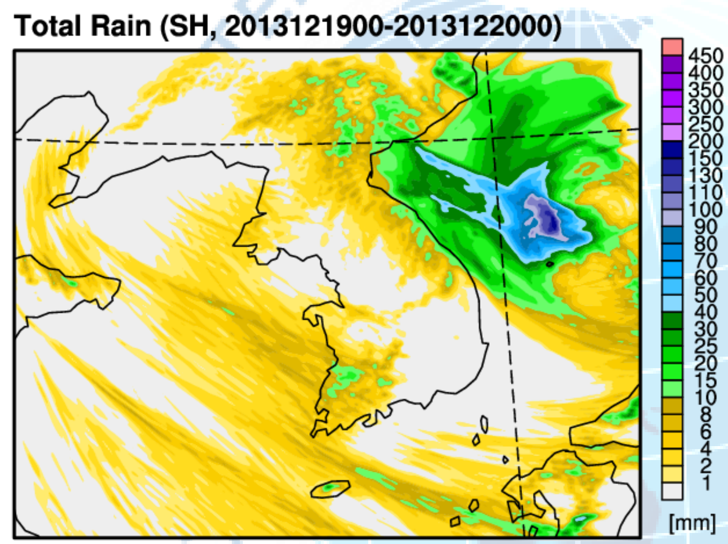
2013.12.20 00 UTC







Precipitation

	Observation	Simulation : SH_3km
Precipitation rate (2013.12.19-20)		
24h-accumulated precipitation (2013.12.19-20)		

Bias = 4.409, RMSE = 13.454, PC = 0.035

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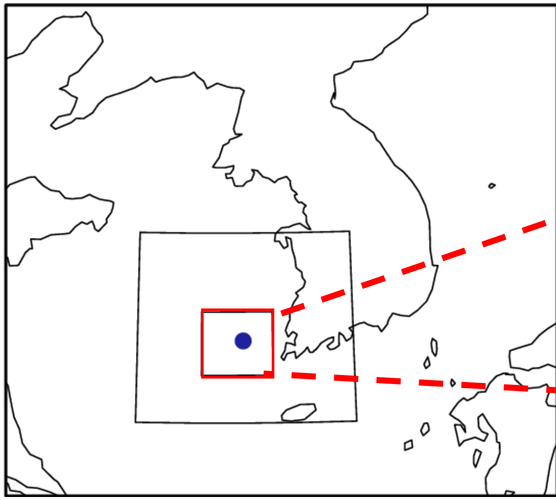
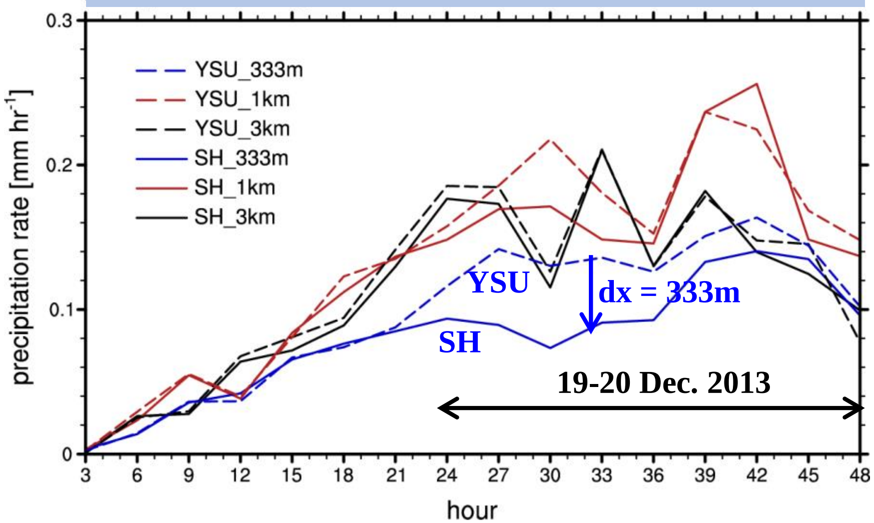
24-h accumulated precipitation

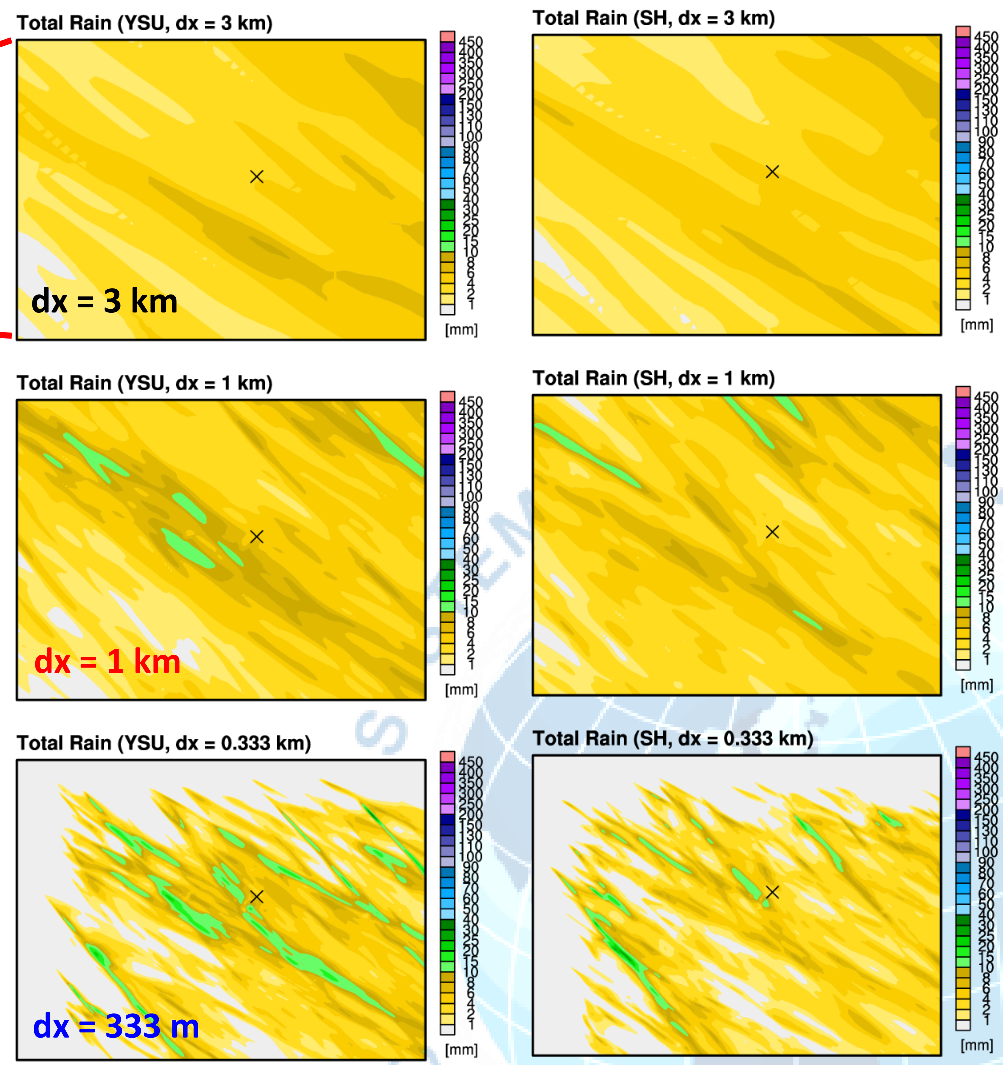


Time series of precipitation rate



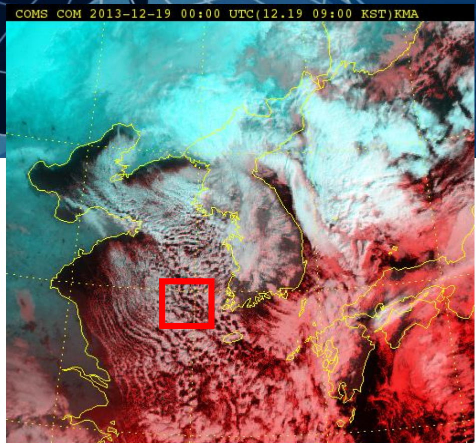
YSU

SH



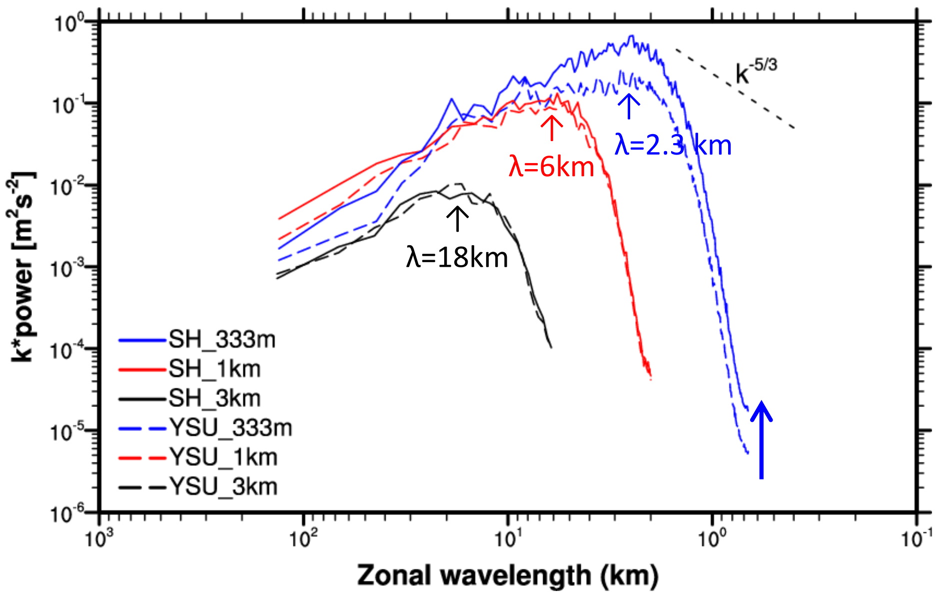
X : Heuksan Island

W at 950 hP (00 UTC 19 Dec 2013)

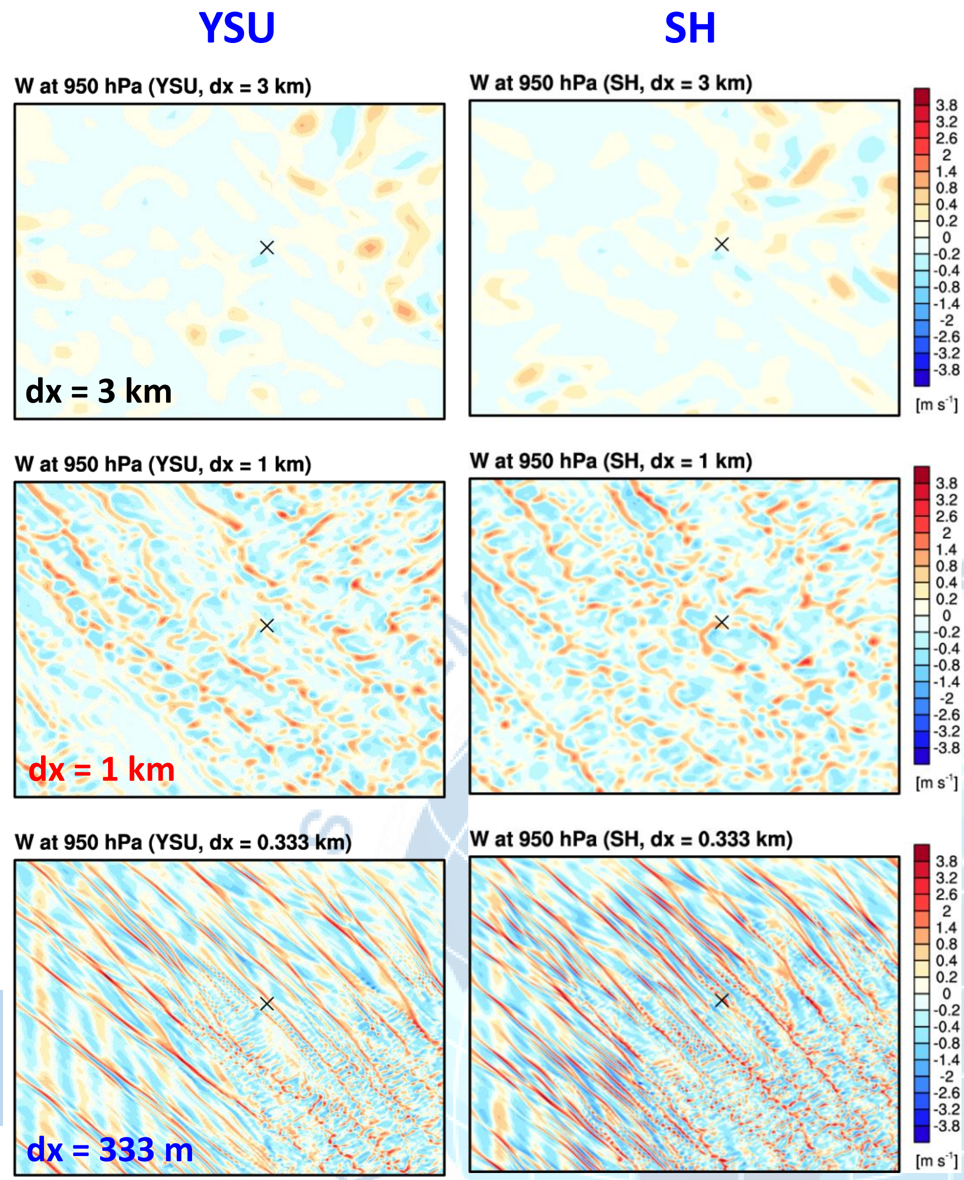


The differences between YSU and SH are pronounced at dx = 333 m

Power spectra of W at 950 hPa



- **dx=3 km → 333m** : Power increases at small scales
- **YSU → SH at 333 m** : Power increases



X : Heuksan Island

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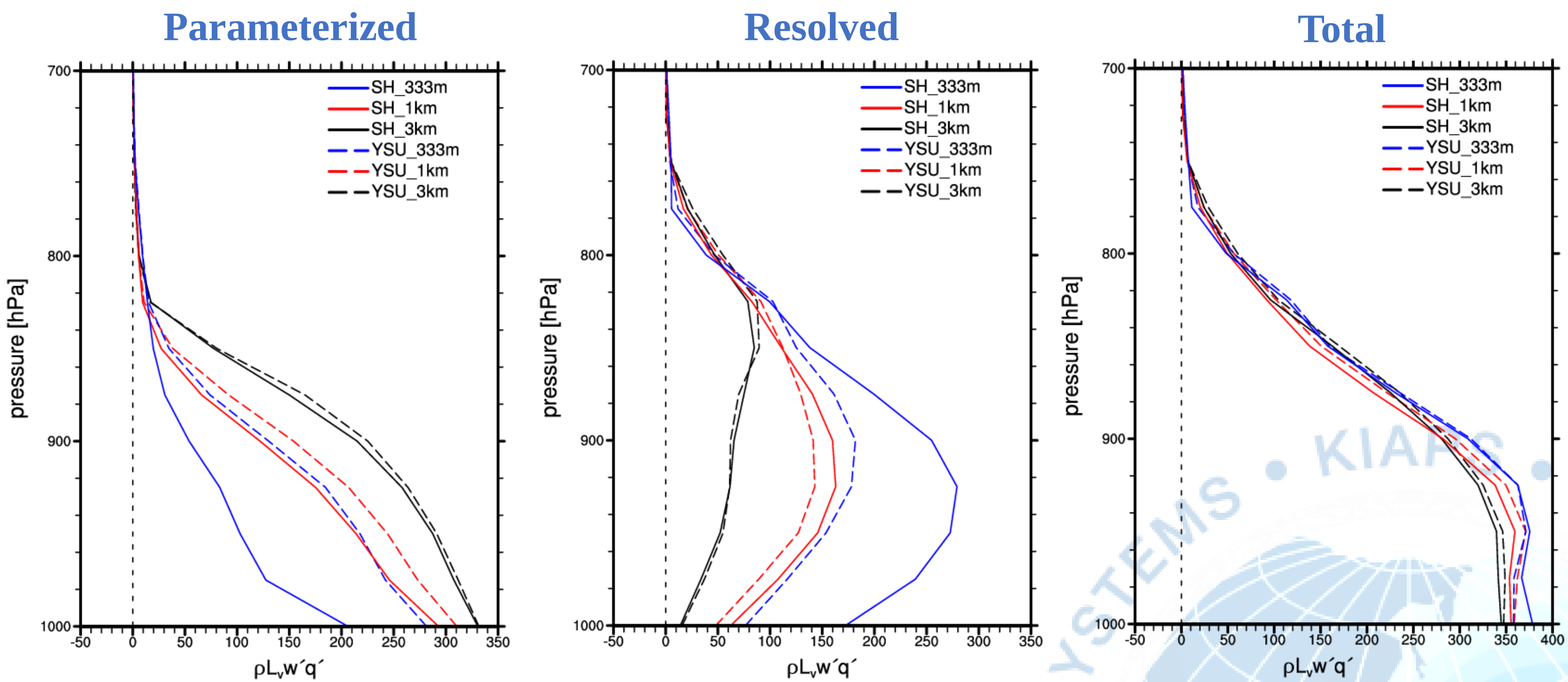
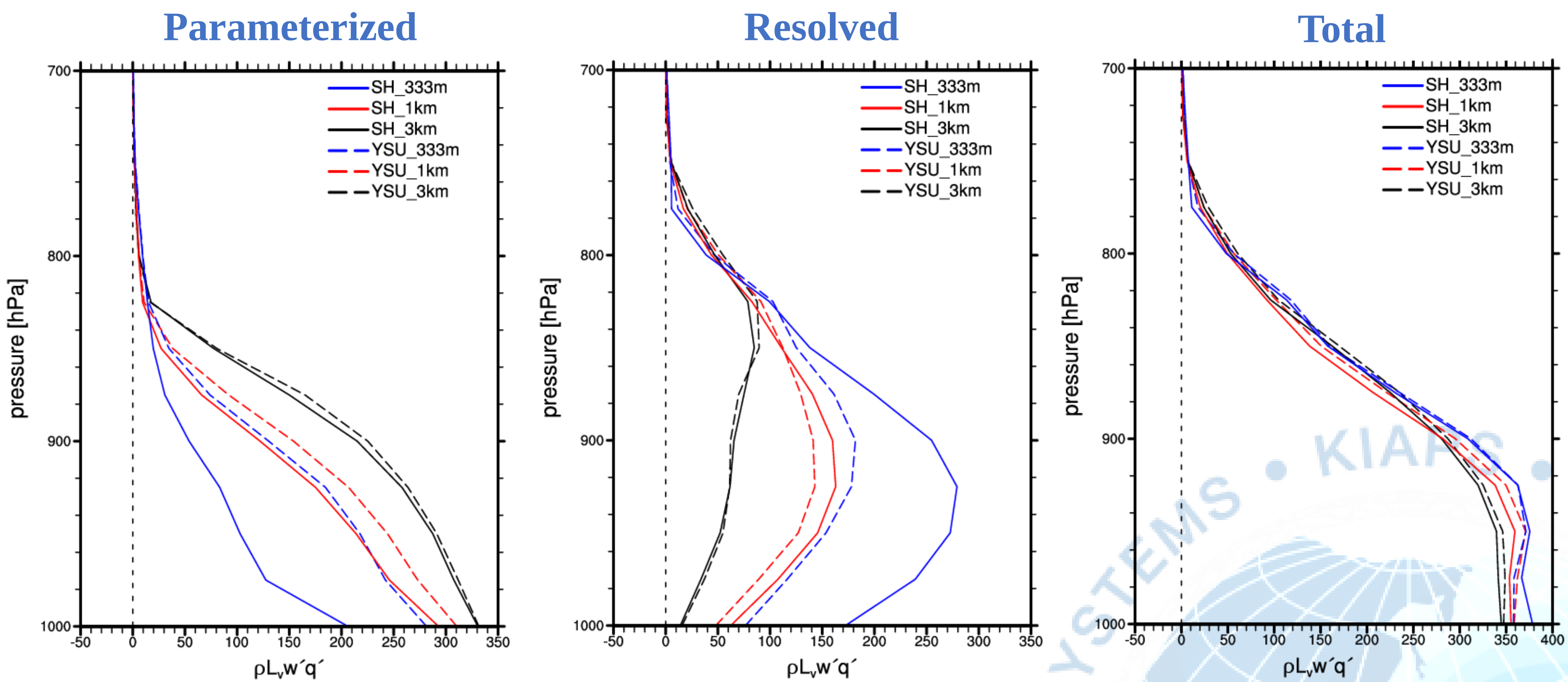
Turbulent moisture flux (00 UTC 19 Dec. 2013)



	Parameterized	Resolved	Total
dx = 3 km → 333 m	↓	↑	↑

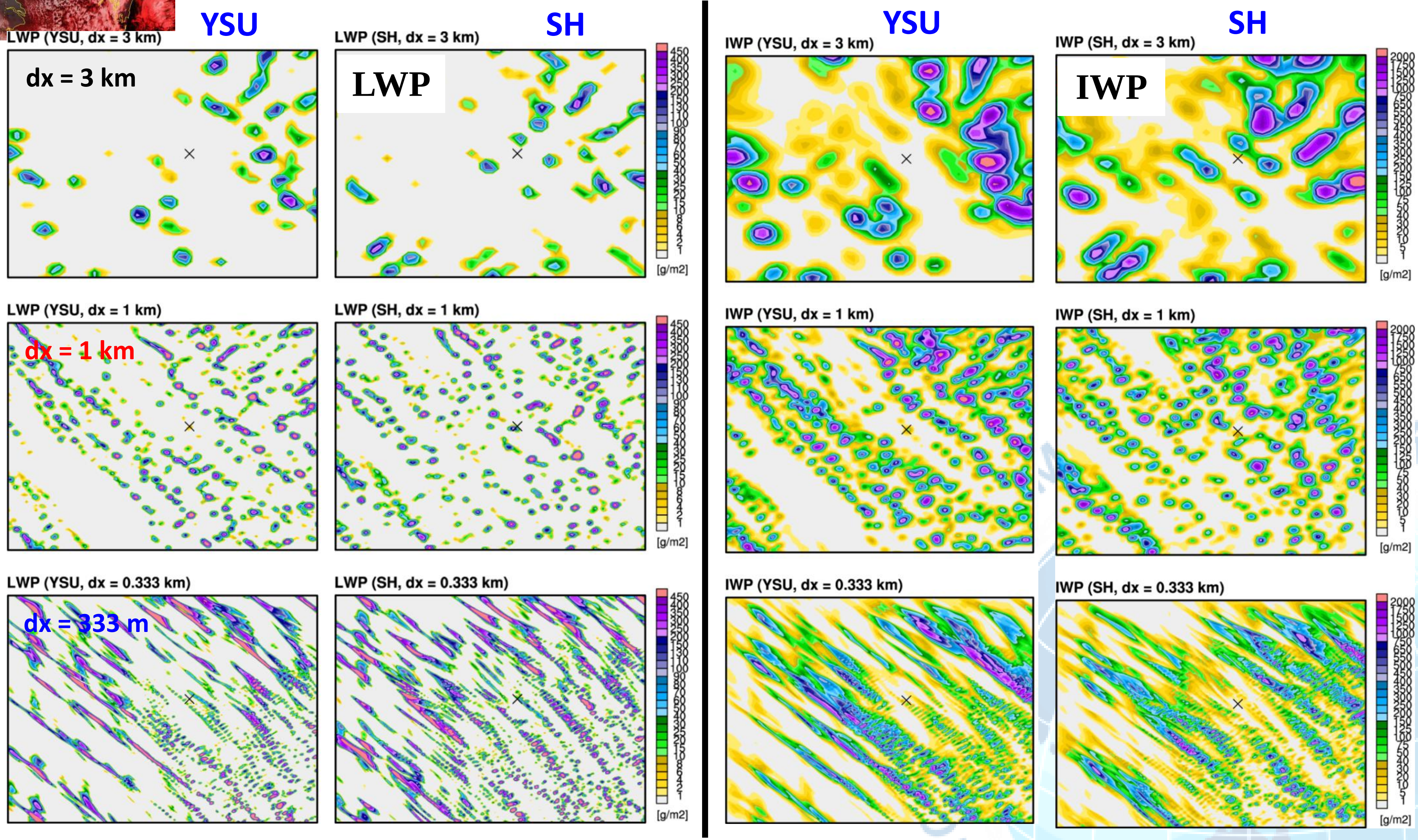
As resolution increases, **parameterized turbulent flux** is largely reduced, but **resolved flux** increases more significantly, and thus **total flux** increases

Turbulent moisture flux (00 UTC 19 Dec. 2013)



		Parameterized	Resolved	Total
YSU→SH	dx = 3 km	↓	-	↓
	dx = 1 km	↓	↑	↓
	dx = 333 m	↓	↑	↑

LWP & IWP (00 UTC 19 Dec. 2013)



Wave-like cloud develops at dx = 333 m

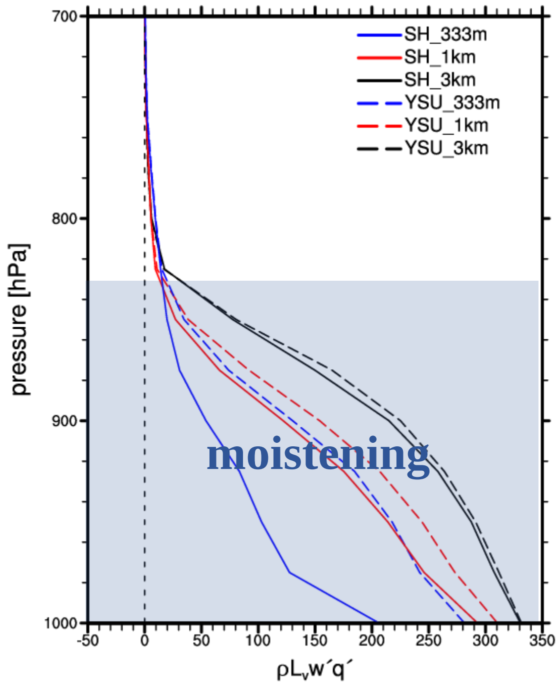
Why surface precipitation decreases

in SH over YSU PBL at 333 m ?

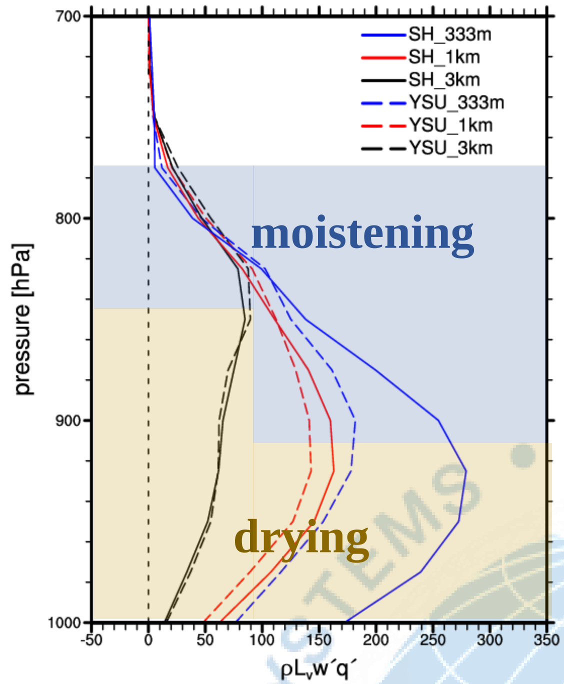
Turbulent moisture flux (00 UTC 19 Dec. 2013)

$$\frac{\partial q}{\partial t} \sim -\frac{\partial \overline{w'q'}}{\partial z}$$

Parameterized



Resolved

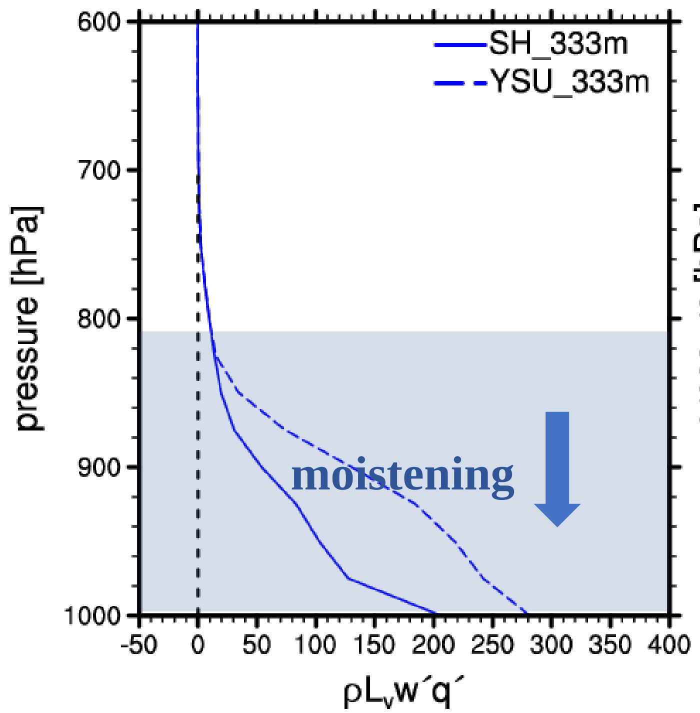


	Parameterized	Resolved
dx = 3 km ➔ 333 m	Reduced vertical gradient of moisture flux ➔ Drying	Increased vertical gradient of moisture flux ➔ Drying below ~900 hPa & Moistening above it

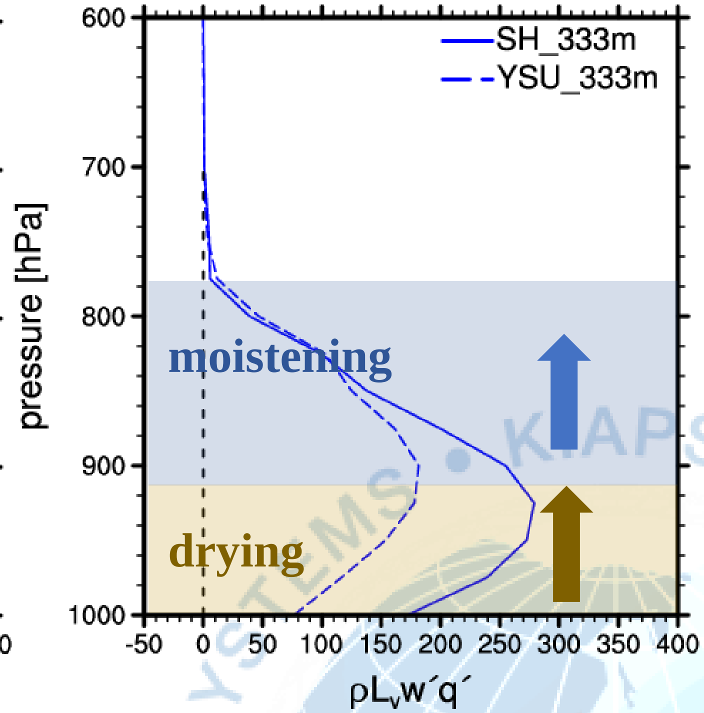
Turbulent moisture flux (00 UTC 19 Dec. 2013)

$$\frac{\partial q}{\partial t} \sim -\frac{\partial \overline{w'q'}}{\partial z}$$

Parameterized

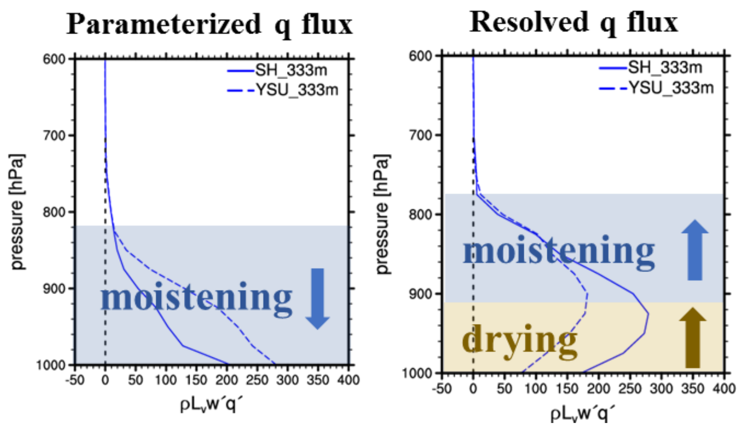


Resolved



	Parameterized	Resolved
YSU → SH at dx = 333 m	Reduced vertical gradient of moisture flux → Drying	Increased vertical gradient of moisture flux → Drying below ~900 hPa & Moistening above it

Effects on precipitation (dx = 333 m)



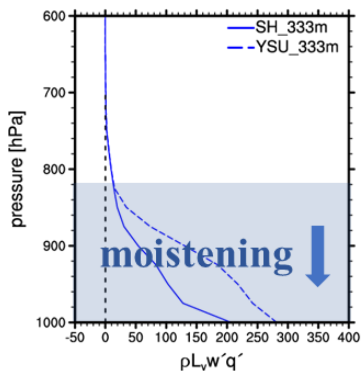
YSU → SH at dx = 333 m

decreased vertical gradient of parameterized moisture flux	increased vertical gradient of resolved moisture flux
↓	↓

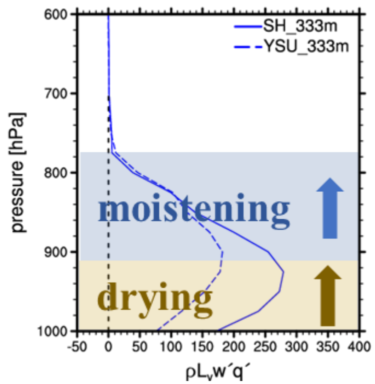
stronger vertical mixing of moisture

Effects on precipitation (dx = 333 m)

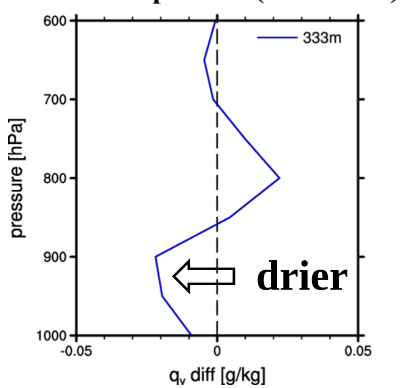
Parameterized q flux



Resolved q flux



Water vapor diff (SH – YSU)



YSU → SH at dx = 333 m

decreased vertical gradient of parameterized moisture flux	increased vertical gradient of resolved moisture flux

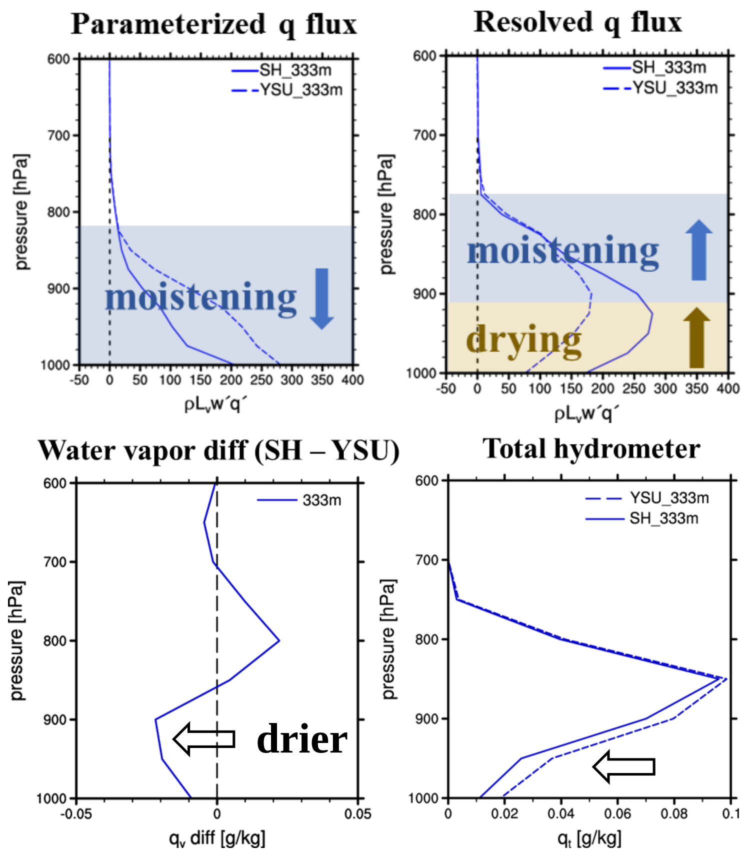
↓ ↓

stronger vertical mixing of moisture

↓

drier low-levels

Effects on precipitation (dx = 333 m)



YSU → SH at dx = 333 m

decreased vertical gradient of parameterized moisture flux	increased vertical gradient of resolved moisture flux

↓ ↓

stronger vertical mixing of moisture

↓

drier low-levels

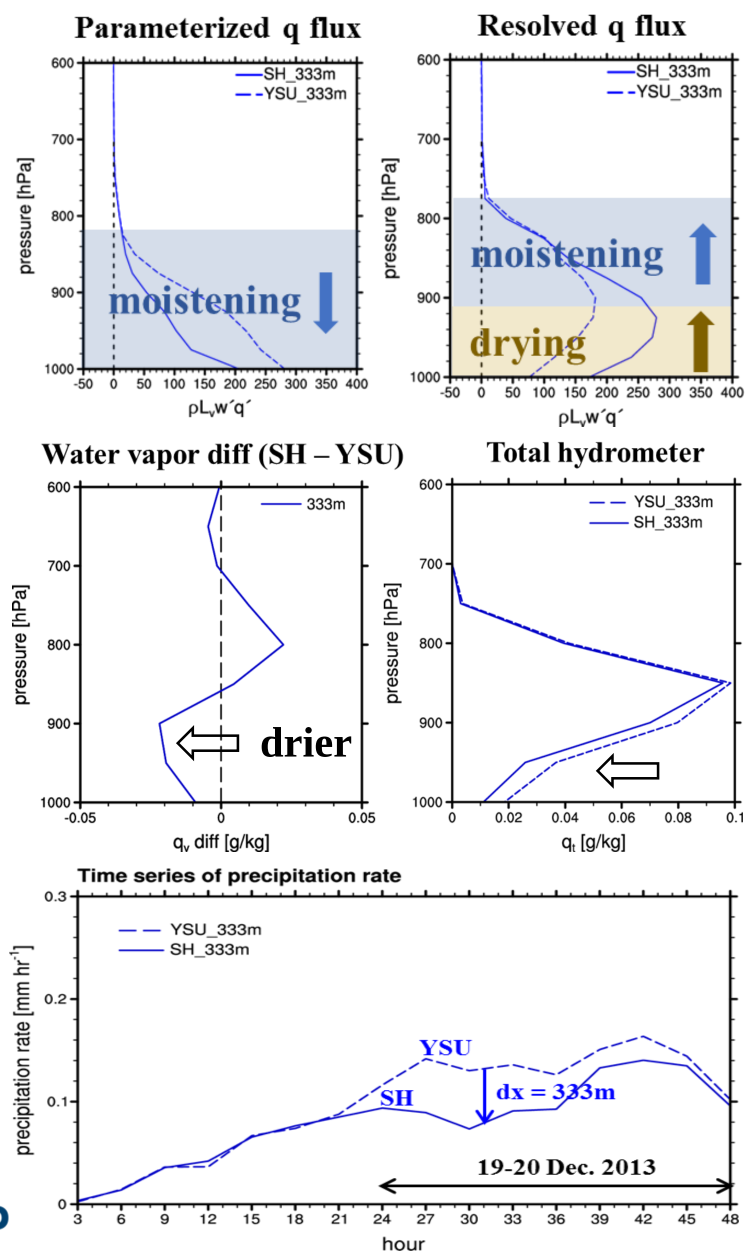
↓

increased evaporation	decreased total hydrometeor (mostly snow)

↓

decreased melting of snow

Effects on precipitation (dx = 333 m)



YSU → SH at dx = 333 m

decreased vertical gradient of parameterized moisture flux	increased vertical gradient of resolved moisture flux

↓ ↓

stronger vertical mixing of moisture

↓

drier low-levels

↓

increased evaporation	decreased total hydrometeor (mostly snow)

↓

decreased melting of snow

↓

decrease in precipitation

KIAP


Korea Institute of Atmospheric Prediction Systems
:Beyond the limit of the modern science and technology
Thank you
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