Overview of the KIAPS's next generation global model

KIM (Korean Integrated Model)

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Korea Institute of Atmospheric Prediction Systems (KIAPS)

Hong and Coauthors, 2018: The Korean Integrated Model(KIM) system global weather forecasting. *Asia-Pac, J. Atmos. Sci.*, **54**, 267-292

Contents

Overview of KIAPS

❒ **Purpose** : Developing a next generation global operational modeling for KMA (KIM)

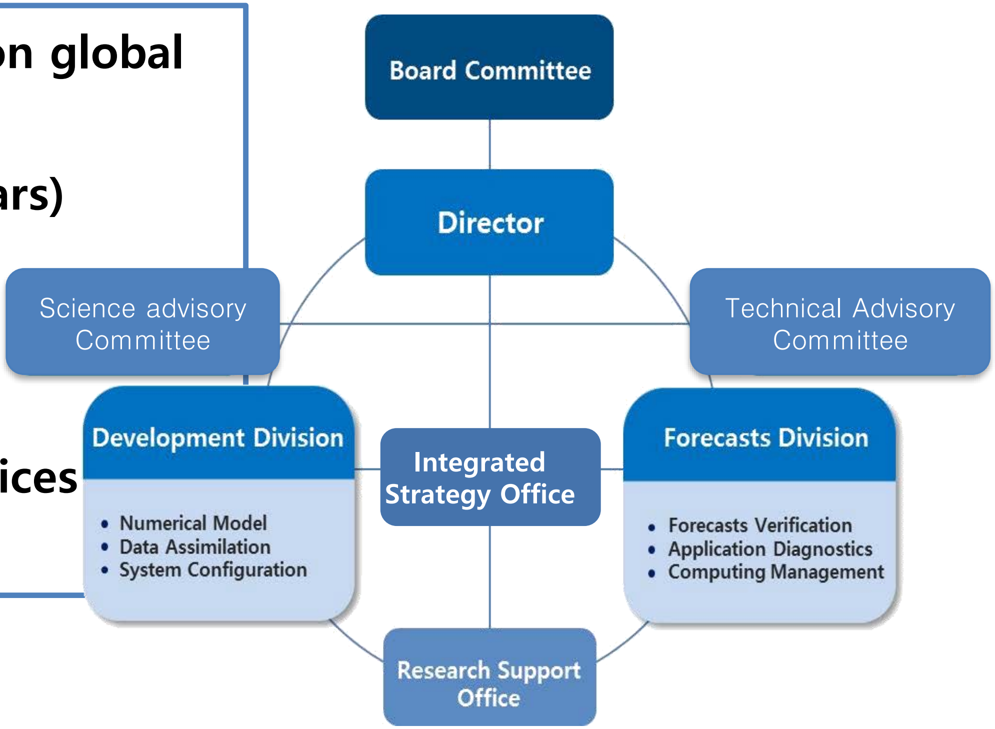
❒ **Project period** : 2011~2019(total 9 years)

❒ **Total Budget**: $95 million

2018 budget -$9 million

❒ **KIAPS is founded at Feb. 15th 2011**

- organization: 2divisions, 6teams, 2offices
- Man power: 58



Significance of KIM:

▶ Removal of scientific and technological dependency on foreign countries

▶ Scientific basis for improving weather phenomena unique to Korean Peninsula

▶ facilitating feedback between forecasters and model developers

Dynamic Core

Representing vertical/horizontal circulations of atmosphere
e.g. advections, pressure gradient force, horizontal diffusion
(adiabatic processes)

→ no net energy source or sink, so conservation is important
spatial/temporal discretization method with grid projection

Overview of KIM dynamic core

"The first fully functional non-hydrostatic spectral element global dynamic core over cubed sphere grid" Joseph Klemp (NCAR)

horizontal discretization:
spectral element on cubed sphere

vertical discretization:
finite difference on hybrid sigma-P

temporal discretization: split-explicit RK3

governing equations:
WRF-type non-hydrostatic

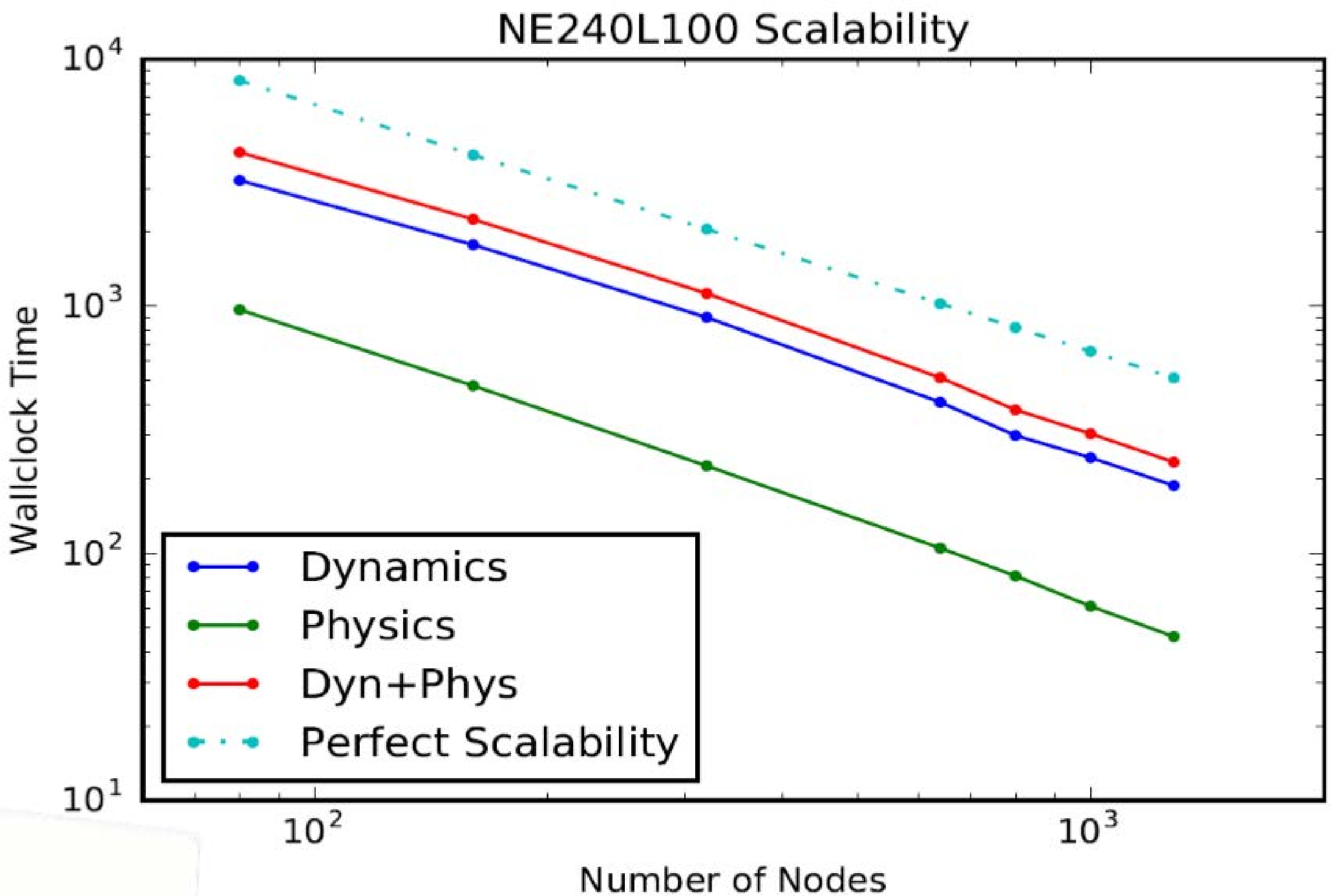
horizontal diffusion:
6^{th} order time-split explicit diffusion

NE240 L91 (dx~12km) model top 1Pa (~80km)

Advantages of the cubed sphere: avoid polar singularity, scalability

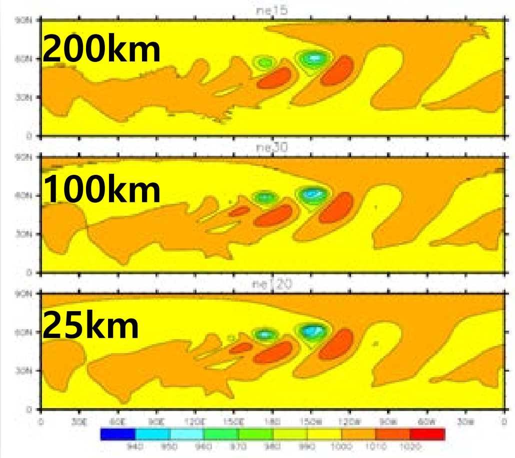
Disadvantages: numerical noise along the edges, computational expensive

The results of KIM scalability test



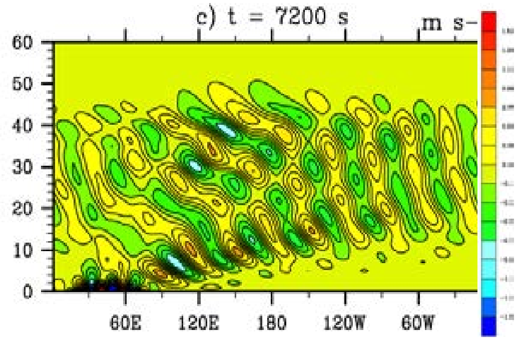
Development of Non-hydrostatic Dyn. (DCMIP)

Baroclinic instability, Ps (9-days)

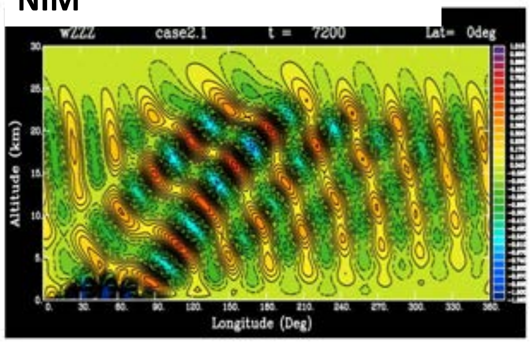


Schär mountain gravity wave in reduced Earth (X=500)

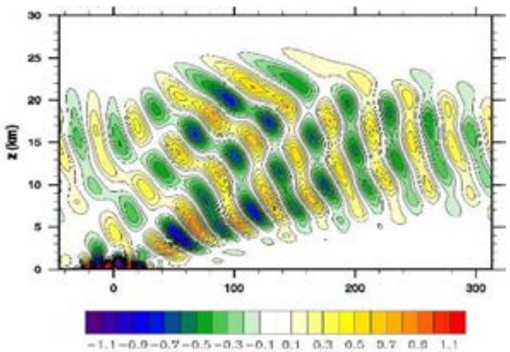
ENDGame



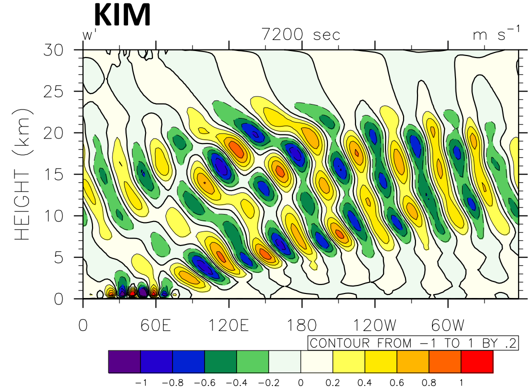
NIM



MPAS



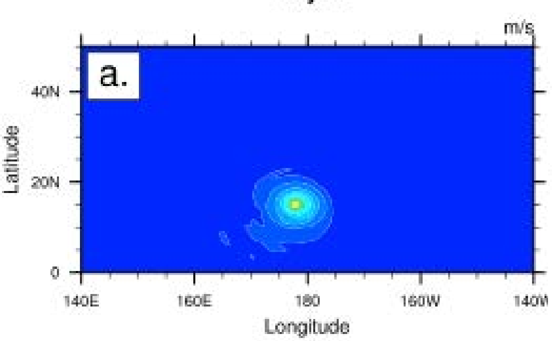
KIM



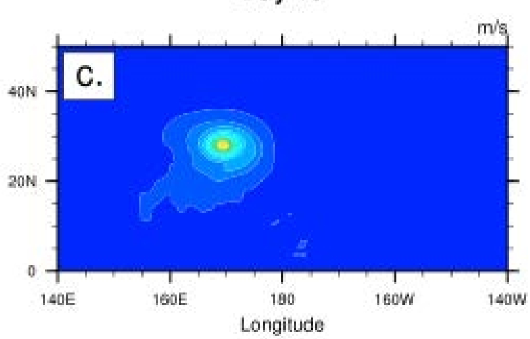
https://www.earthsystemcog.org/projects/dcmip-2012/Test_Cases/results_by_mc

- **Idealized tropical cyclone with simplified physical forcings**

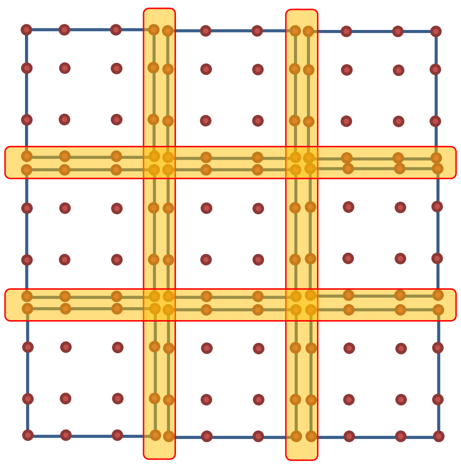
Day 3



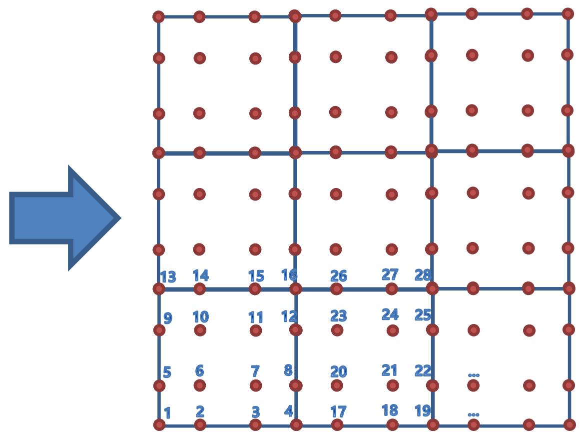
Day 10



Algorithmic Change
EP-based → UP_based



Entire Point (EP)



Unique point (UP)

The shared points between different elements ('Yellow Area') consider as one point

- Maximum rate of Calculation reduction is #UP/#EP=9/16= 0.5625
- Derivative operator is changed to matrix-vector multiplication
  - Multi-loop for elements is vanished.
- Direct Stiffness summation is included in the matrix
  - Further enhance the efficiency

Physics

Representing change of atmospheric thermodynamic status
e.g. air temperature, humidity, precipitation (diabatic processes)

→ net energy source or sink to air: causes of weather

KIM3.0 Physics (2017.4)

	Scheme	Updated	Reference
Radiation (복사)	Revised RAD (RRTMK)	• unified RRTMG • reduced MCICA • updated ancillaries (aerosol, GMAO ozone, reflectivity, emissivity, snow albedo) • Improved two-stream approximation for shortwave radiation • Scale-awareness for sub-grid hydrometeors	Iacono et al. 2008 **Beak 2017**
Land surface (지면)	Revised LSM	• 3-layer sea-ice model • frozen processes (z0, conductivity over snow cover, flux over sea-ice) • USGS to IGBP for land data • soil moisture initialization • consistent diffusivity in LSM and RAD • Heterogeneous land-surface parametrization • Roughness length considering snow	Ek et al. 2003 **Koo et al. 2016**
Ocean surface layer (해수면)	Diurnal SST OSH	• SST warming effect • Considering salinity effect	Kim and Hong 2010 **Lee and Hong 2017**
Boundary layer (경계층)	Scale-aware non-local PBL	• top-down mixing • updated background diffusion & heating rate • minimum Richardson number changed • scale-aware (ShingHong PBL) • Considering dissipative heating	Hong et al. 2006 **Shin and Hong 2015** **Lee et al. 2016**
Gravity wave drag (중력파)	Sub-grid orographic GWD	• flow blocking drag • orographic anisotropy • updated efficiency/intermittency factor	Hong et al., 2008 **Choi and Hong 2015**
	Non-orographic GWD	• Source-based spectral nonorographic GWD	**Choi et al. 2017**
Deep convection (깊은대류)	Scale-aware mass-flux CPS	• revised autoconversion & entrainment rate • moisture-based trigger threshold • scale-aware / aerosol-aware	Han and Pan 2011 Lim et al. 2014 **Han et al. 2016** **Kwon and Hong 2016**
Shallow convection (얕은대류)	Adjustment SCV	• improved eddy diffusivity profile (2.5) • Considering diffusion of cloud water contents	Hong et al. 2013
Microphysics (미세물리)	WSM5 MPS	• effective radius	**Hong et al. 2004** **Bae et al. 2016**
Cloudiness (운량)	Prognostic CLD	• revised CPS condensate • consistency (cloud-MPS-CPS-RAD) • reduced high cloud fraction at high latitude	**Park et al. 2016**

CPS

- **The grid-size dependency is considered (scale-aware scheme)**

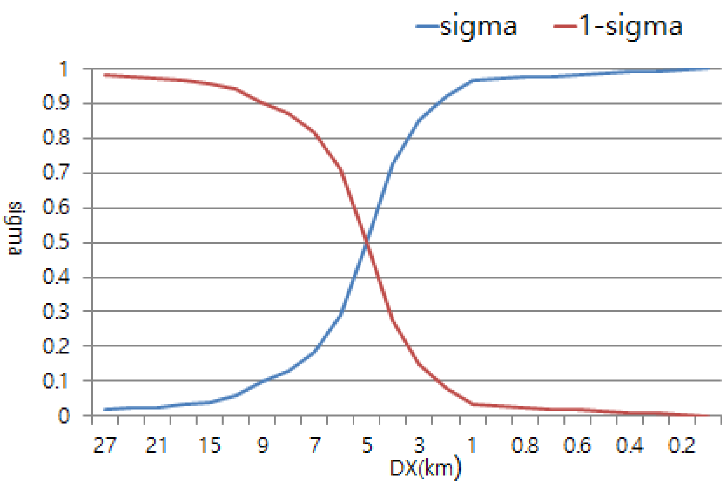
$$\sigma = 1 - \frac{1}{\pi}\left\{\tan^{-1}\left[\sigma_{con}\left(\Delta x - \Delta x_{5km}\right)\right] + \frac{\pi}{2}\right\}$$

$$\text{where} \quad \sigma_{con} = \frac{\tan(0.4\pi)}{\Delta x_{5km} - \Delta x_{1km}}$$

Adapted from Hong and Pan (1998, MWR)

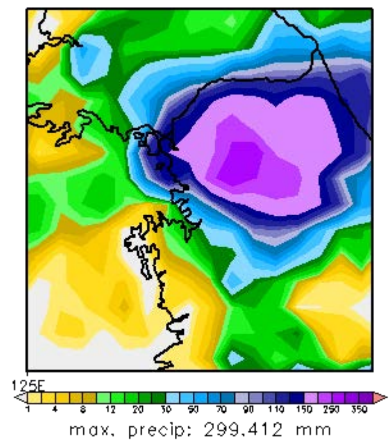
Δx	σ
9 km	0.1
5 km	0.5
1 km	0.9

- **Cloud-base mass flux** [∝ $(1 - \sigma)^2$]
- **Convective Inhibition** (∝ (1-σ))
- **Moisture detrained to grid scale** (∝ σ)

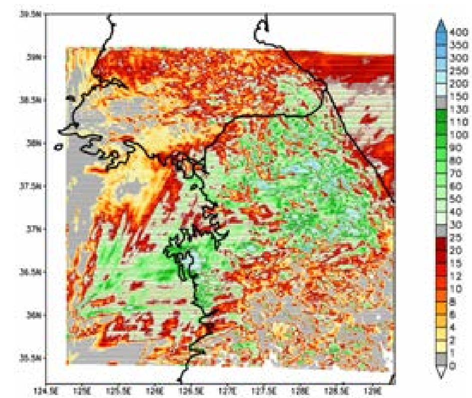


24-h accumulated precipitation

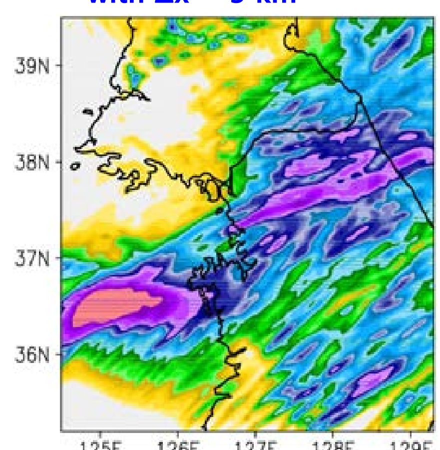
TMPA



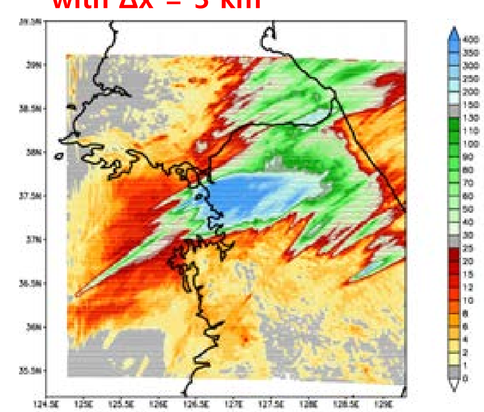
Original SAS in the domain with Δx = 3 km



No CPS in the domain with Δx = 3 km



Modified SAS in the domain with Δx = 3 km



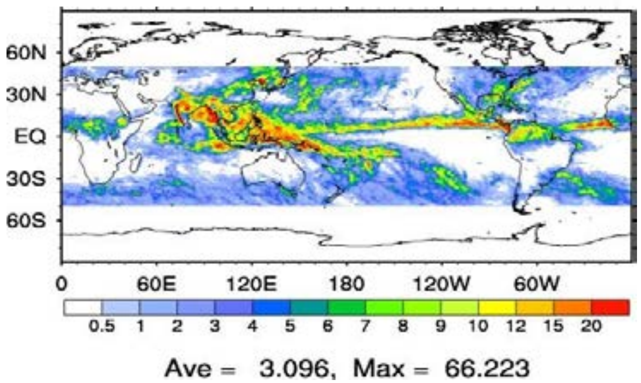
Evaporation over Ocean

- To apply the saturated vapor pressure for seawater over ocean

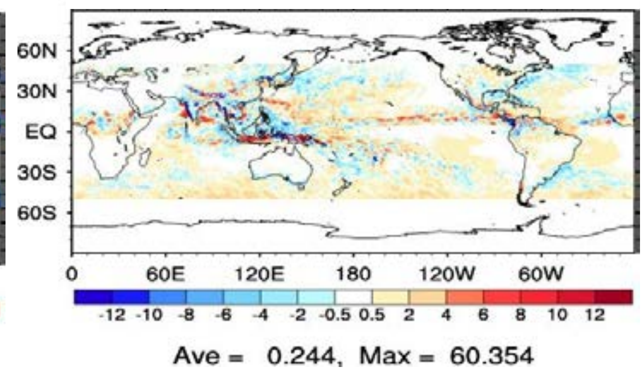
  Global sea surface salinity ~ 32-38 ‰

Improvement of light rain forecasting

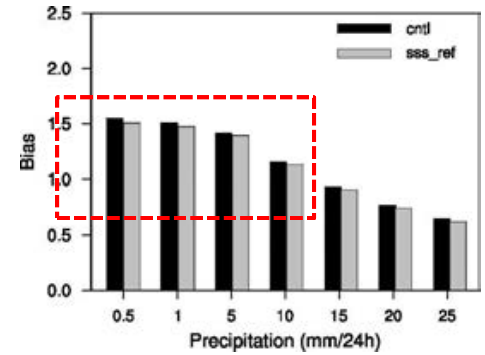
TMPA



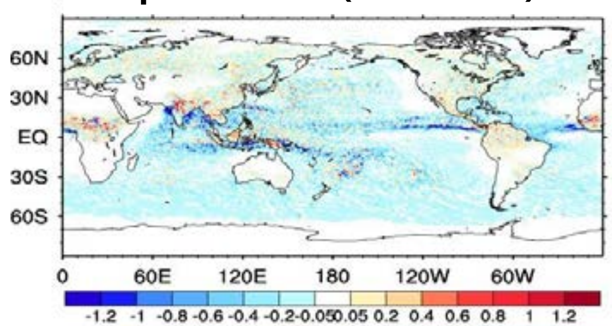
Prcp Bias (CTL – TMPA)



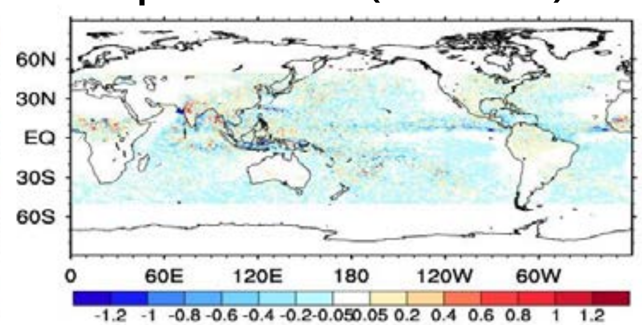
BIAS for Jul 2013



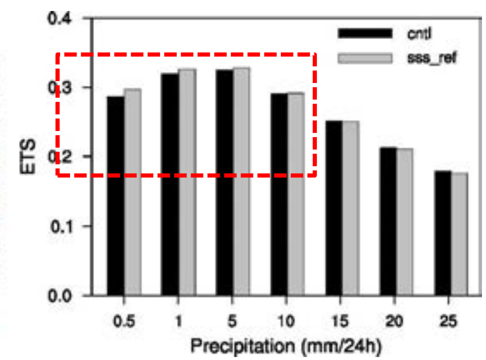
Prcp Bias Diff (SSS – CTL)



Prcp RMSE Diff (SSS – CTL)



ETS for Jul 2013



Lee and Hong (under review)

Data Assimilation

Accurately representing the current status (or initial condition) of the atmosphere

→ Time tendency calculated by dynamics and physics will be added to predict future weather

Observation data used in KMA and KIAPS assimilation system

Observation type		KMA	KIAPS	Observation type		KMA	KIAPS
1	SONDE	○	○	9	IASI	○	○
2	SURFACE	○	○	10	CrIS	○	○
3	AIRCRAFT	○	○	11	ATMS	○	○
4	SCATWIND	○	○	12	AMV	○	○
5	HIRS	○	×	13	GPS-RO	○	○
6	AMSU-A	○	○	14	CSR	○	○
7	MHS	○	○	15	SSMIS	×	○
8	AIRS	○	×	16	TC bogus	○	○

SCATWIND: Scatterometer wind

HIRS: High-resolution Infrared Radiation Sounder

AMSU-A: Advanced Microwave Sounding Unit-A

MHS: Microwave Humidity Sounder

AIRS: Atmospheric Infrared Sounder

IASI: Infrared Atmospheric Sounding Interferometer

CrIS: Cross-track Infared Sounder

ATMS: Advanced Technology Microwave Sounder

AMV: Atmospheric Motion Vector

GPS-RO: GPS Radio occultation

CSR: Clear Sky Radiance

SSMIS: Special Sensor Microwave Imager Sounder

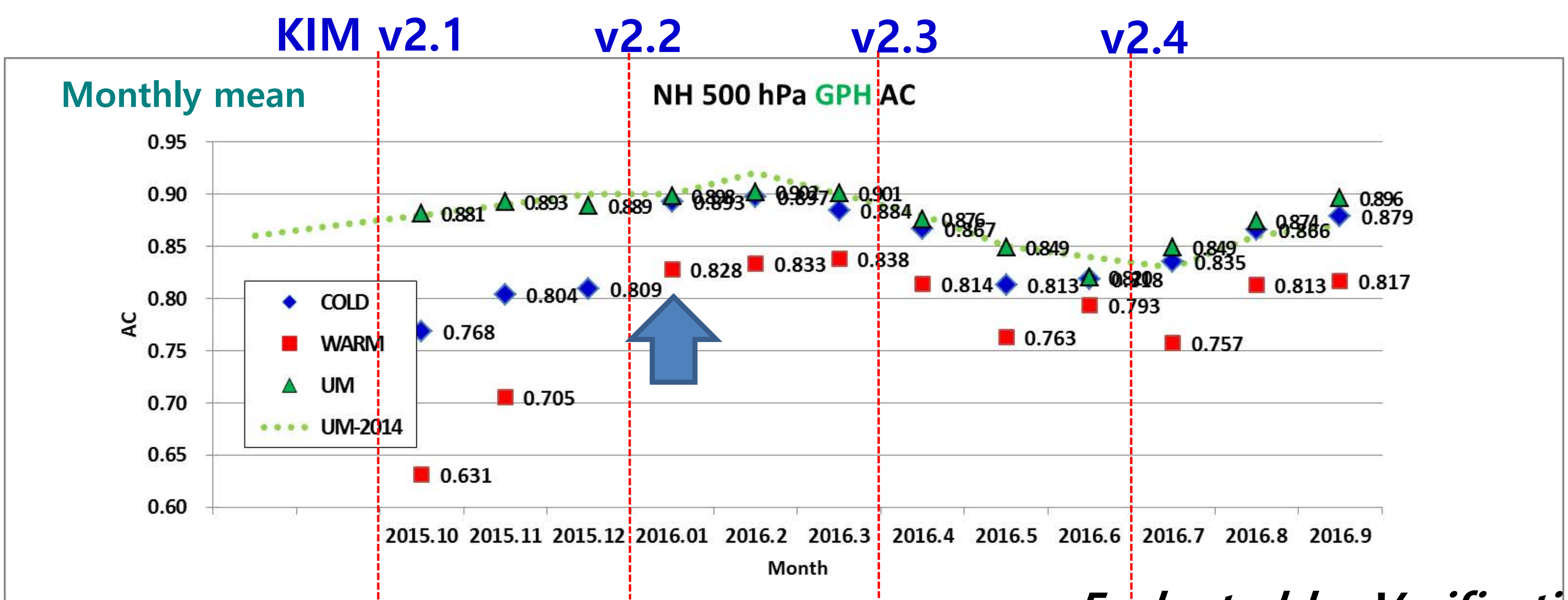
3DVAR

Song and Kwon 2015 (MWR)

- 3DVAR system built on KIM (cubed sphere grid using Real-observations)
- **Spectral transform** as the horizontal Filter
  : Direct transform **from cubed sphere grid to wave space**
- The observation data assimilated so far

Sonde, Surface, Aircraft, AMSU-A, IASI, GPO-RO, AMV, ATMS, CrIS, MHS, CSR, ScatWind (12 types)

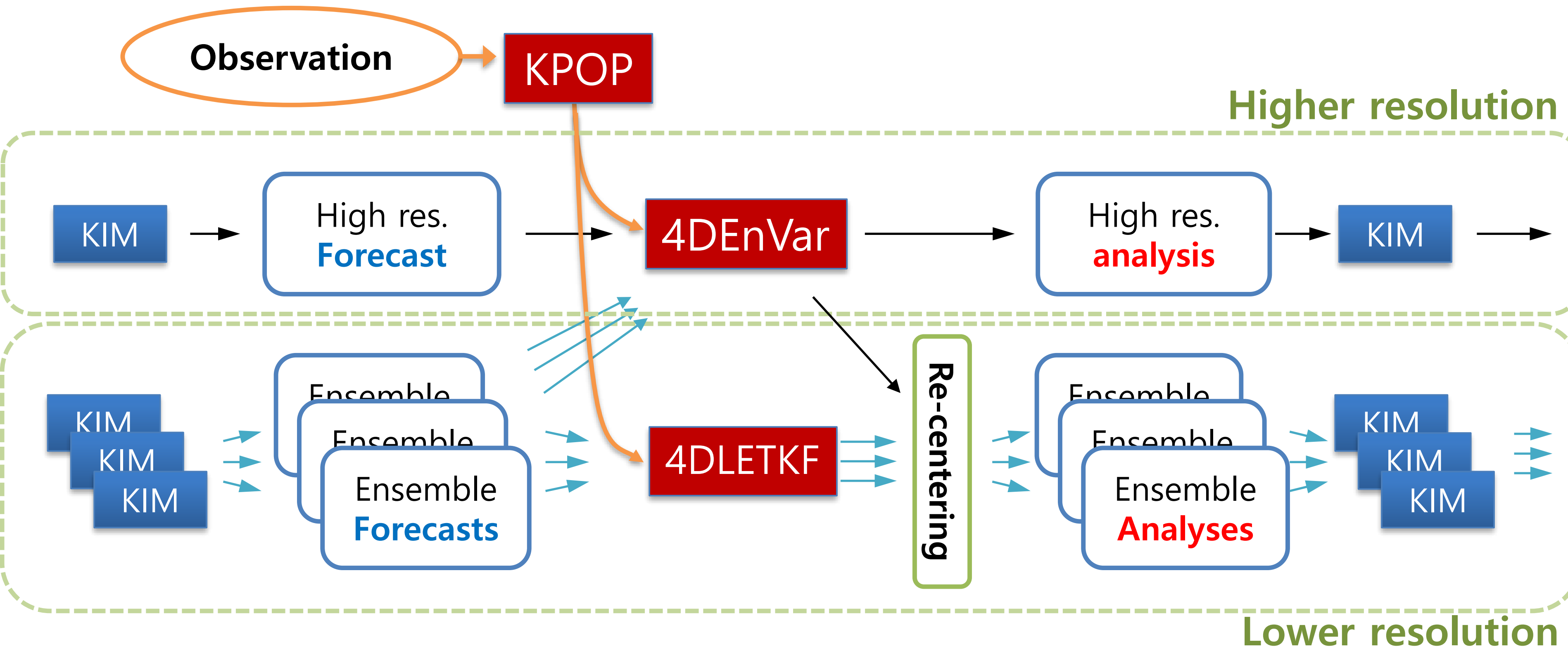
- **Results of 3DVAR system**



Evaluated by Verification Team

Hybrid-4DEnVar (2017 Mar)

- **4DEnVar Forecast System with KIM, KPOP, and 4DLETKF**



KPOP: KIAPS Package for Observation Processing

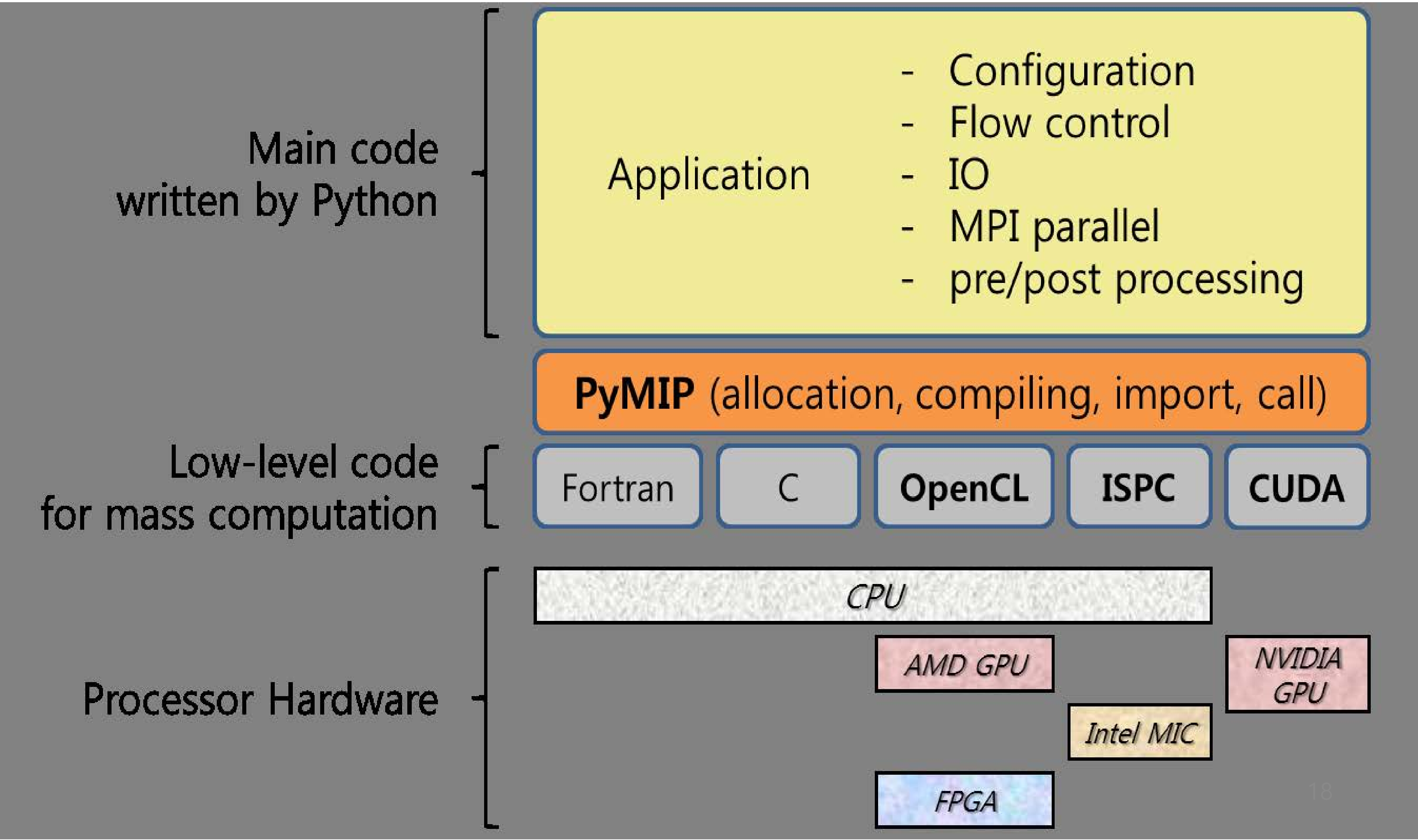
KIM resolution (NE240 ~ 12 km)

Ensemble resolution (NE060 ~ 50 km), 50 members

Analysis resolution (NE060 ~ 50 km)

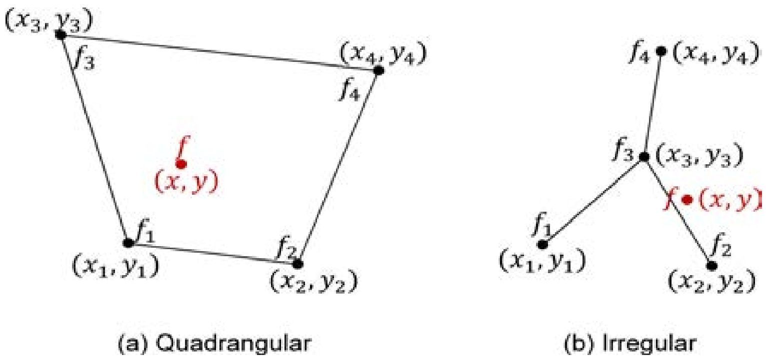
Model Framework and verification results

Multi-platform KIM

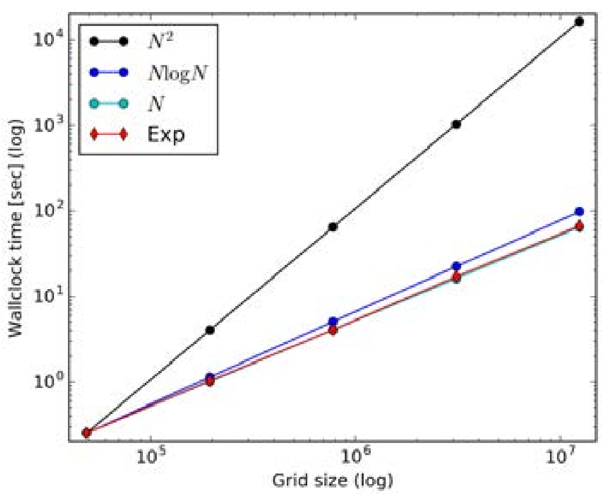


General Bilinear Interpolation between Spherical Grids

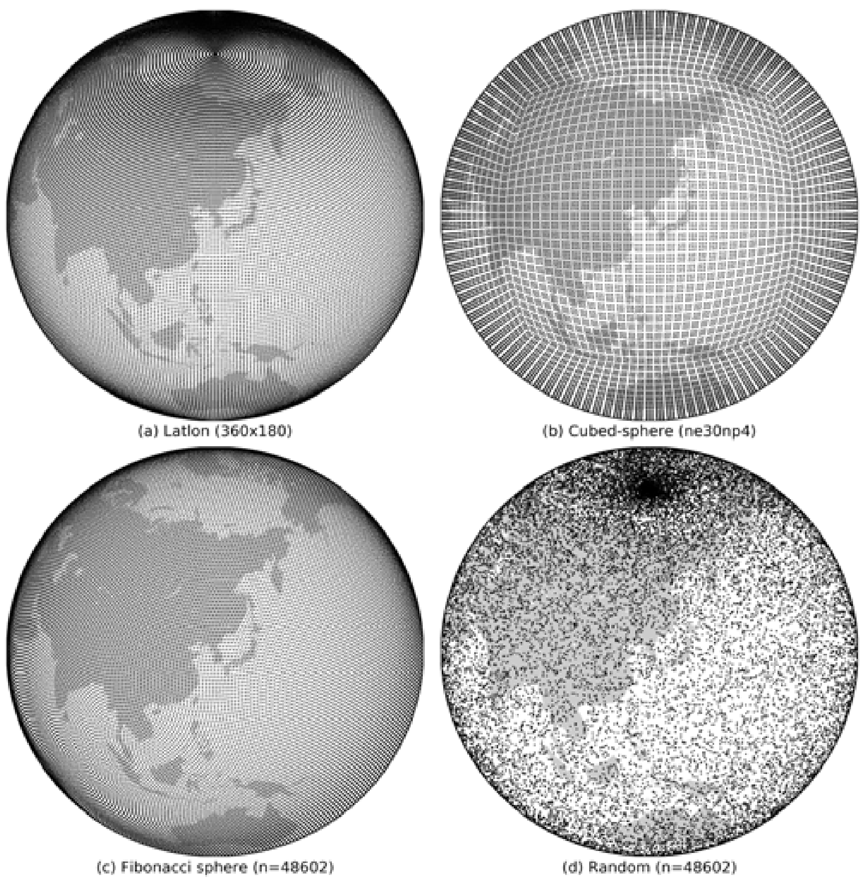
Generalized bilinear interpolation



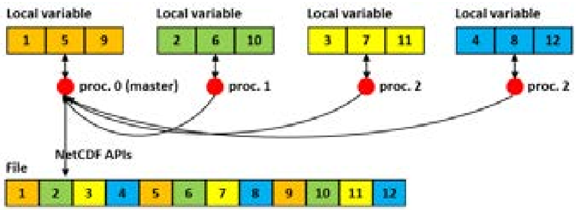
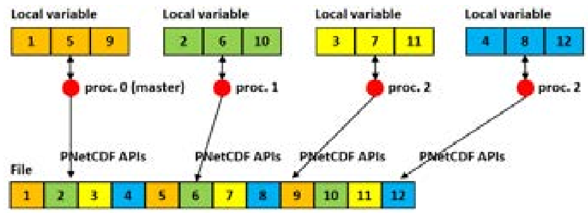
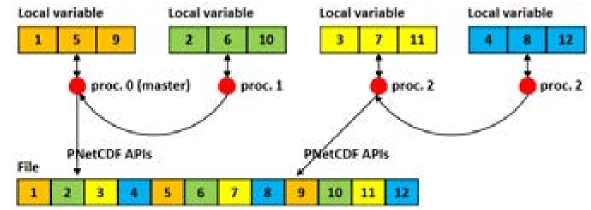
Fast and scalable search algorithm



Remapping between arbitrary spherical grids



Improvement of I/O performance using I/O decomposition method

sequential I/O	parallel I/O	I/O decomposition
		

sequential I/O

- The master process collects all the data and outputs it.
- Using NetCDF APIs

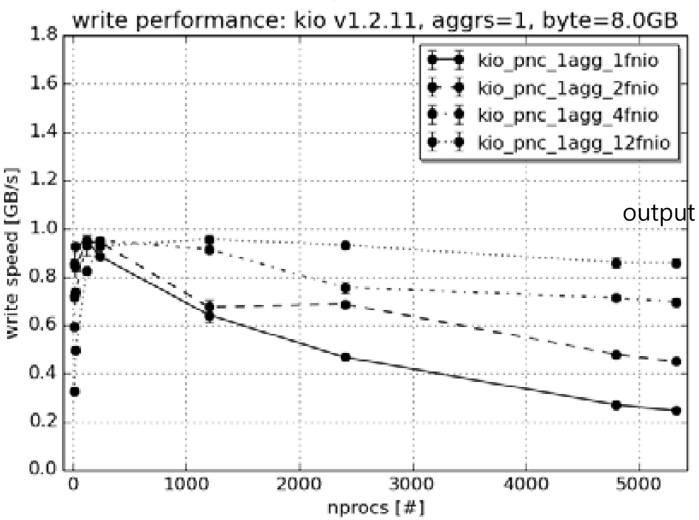
parallel I/O

- All processes access and write the file at the same time.
- Using PNetCDF APIs

I/O decomposition

- Only some processes participate in the output. (output processes)
- Using PNetCDF APIs (only output processes)

@Nuri



output procs	I/O speed
444,	0.86 GB/s (x **3.5**)
1332,	0.70 GB/s
2664,	0.45 GB/s
5328,	0.25 GB/s

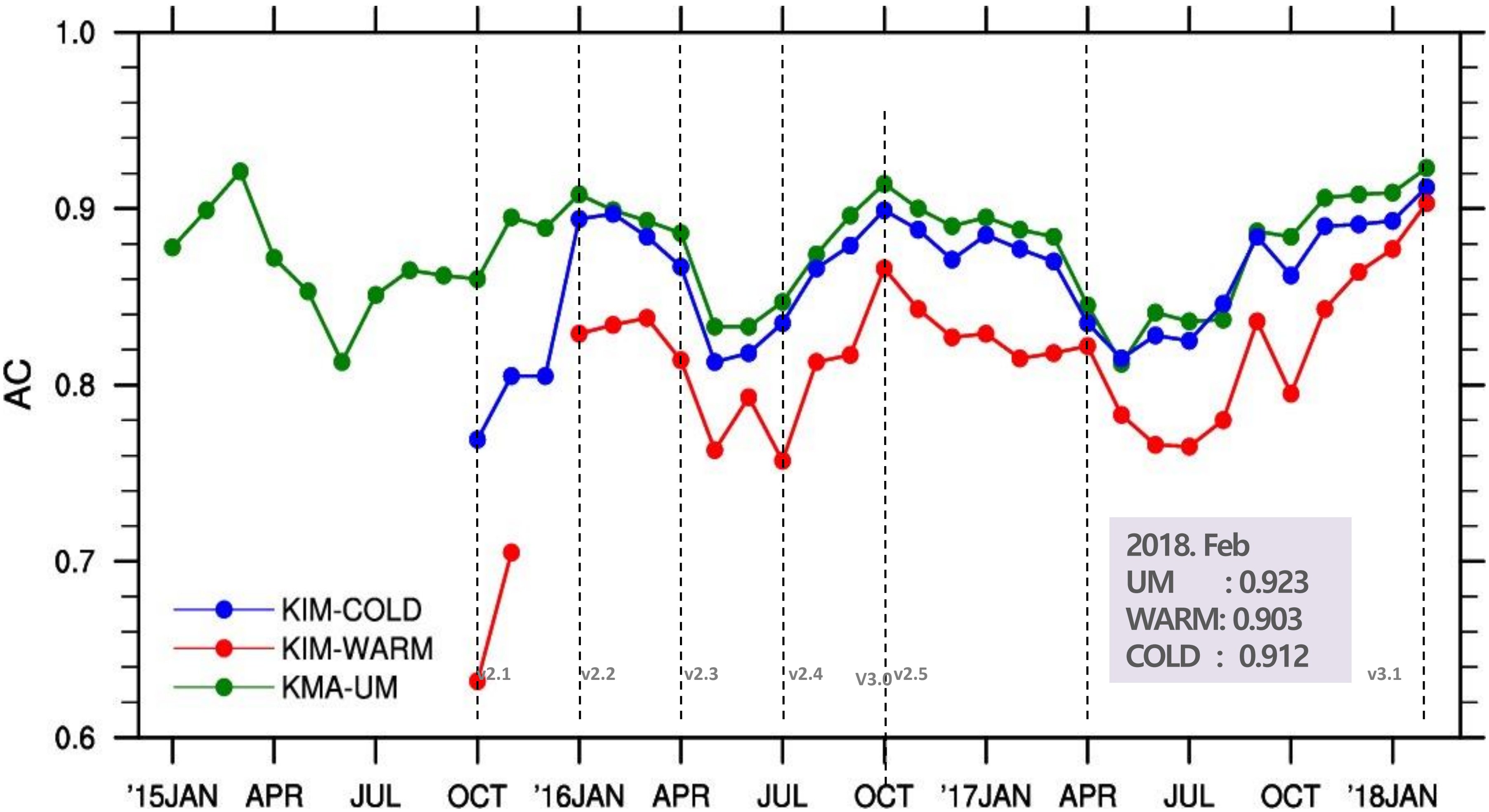
	w/o I/O decomp.	w/ I/O decompo.	speed-up
ncores	10,008		
nios	5,004	139	
total (sec)	14,259 (3h 58m)	12,244 (3h 24m)	**1.16**
write (sec)	1,318 (9.2%)	478 (3.9%)	**2.76**

- When applied to KIM, the performance is improved about 2.76 times in the output and about 1.16 times in the total when compared to the conventional parallel output.

- The # of output processes is set to x1, x1/2, x1/4, x1/12 of the # of total processes.
- With 5,328 processes, it is 3.5 times faster to use 444 processes than to use the entire processes for output.

KIM Real time forecasts skill

500hPa geopotential height anomaly correlation at t=+120h fcst



SUMMARY

▶ Major components of KIM are mostly developed by KIAPS scientists
- dynamic core, physics, data assimilation and model framework

▶ Non-hydrostatic dynamic core and data assimilation system over cubed sphere system are implemented at KIAPS, will be adopted to US/NWS and UK Met Office

▶ Physics suite of KIM has many updates with special emphasis on scale-aware and inter-scheme consistency

▶ Flexible model framework – operable on both CPU & GPU platform, KIM-IO, coupler capability are also developed in KIAPS

▶ The continuous objective and subjective verifications are conducted in order to ensure the improvement of updated model and identify model deficiencies

Korea Institute of Atmospheric Prediction Systems

:Beyond the limit of the modern science and technology

Thank you

KIAPS
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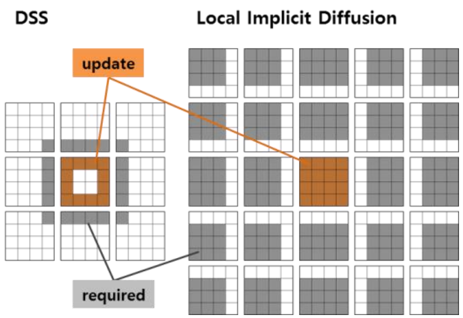
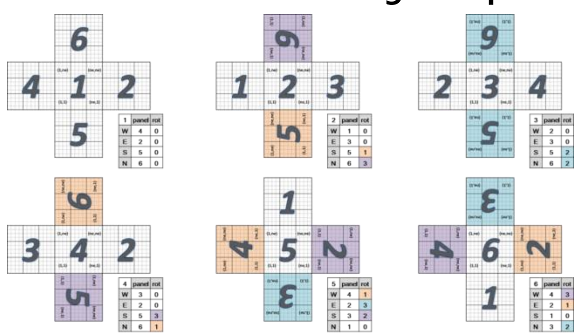
Parallel design for local implicit diffusion   FRAME



- Develop a new parallel design because it requires wider and more complex communications than the DSS

A new algorithm to find a neighbor element/point on the cubed-sphere

(1) Define rotation indices of neighbor panels



(2) Convert index coordinates

Rotation	Return
0	(i, j)
1	(j,n-i+1)
2	(n-i+1,n-j+1)
3	(n-j+1, i)

(3) Find a neighbor using simple arithmetic

A new general-purpose library for MPI point-to-point communications

- Generate index tables automatically for MPI point-to-point communications from a given Source-Destination mapping table

Source-Destination mapping table

source rank	2	2	2	2	2	2	2	2	2	2	2	2	0	1	1	0	1	1	2	2	2	2	2	2
source grid index	1	2	3	1	2	3	2	3	4	2	3	4	3	3	4	3	3	4	3	4	5	3	4	5
destination rank	0	0	0	0	0	0	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2
destination grid index	1	1	1	2	2	2	1	1	1	2	2	2	1	1	1	2	2	2	1	1	1	2	2	2
weight index	4	5	6	5	6	7	4	5	6	5	6	7	1	2	3	2	3	4	4	5	6	5	6	7

send group

destination rank	0			1		
source grid index	1	2	3	2	3	4
send-buffer index	**1**	**2**	**3**	**4**	**5**	**6**

receive group

source rank	0		1			
source grid index	3		3		4	
recv-buffer index	**1**		**2**		**3**	
destination grid index	1	2	1	2	1	2
weight index	1	2	2	3	3	4

local group

source grid index	3		4		5	
destination grid index	1	2	1	2	1	2
weight index	4	5	5	6	6	7

src2send

source grid index	1	2	3	2	3	4
send-buffer index	1	2	3	4	5	6

send_schedule

destination rank	0	1
start index in the send-buffer	1	4
size of the send data	3	3

recv2dst

recv-buffer index	1		2		3	
destination grid index	1	2	1	2	1	2
weight index	1	2	2	3	3	4

recv_schedule

source rank	0	1
start index in the recv-buffer	1	2
size of the receive data	1	2

src2dst

source grid index	3		4		5	
destination grid index	1	2	1	2	1	2
weight index	4	5	5	6	6	7

3DVAR

Song and Kwon 2015 (MWR)

- 3DVAR system built on KIM (cubed sphere grid using Real-observations)

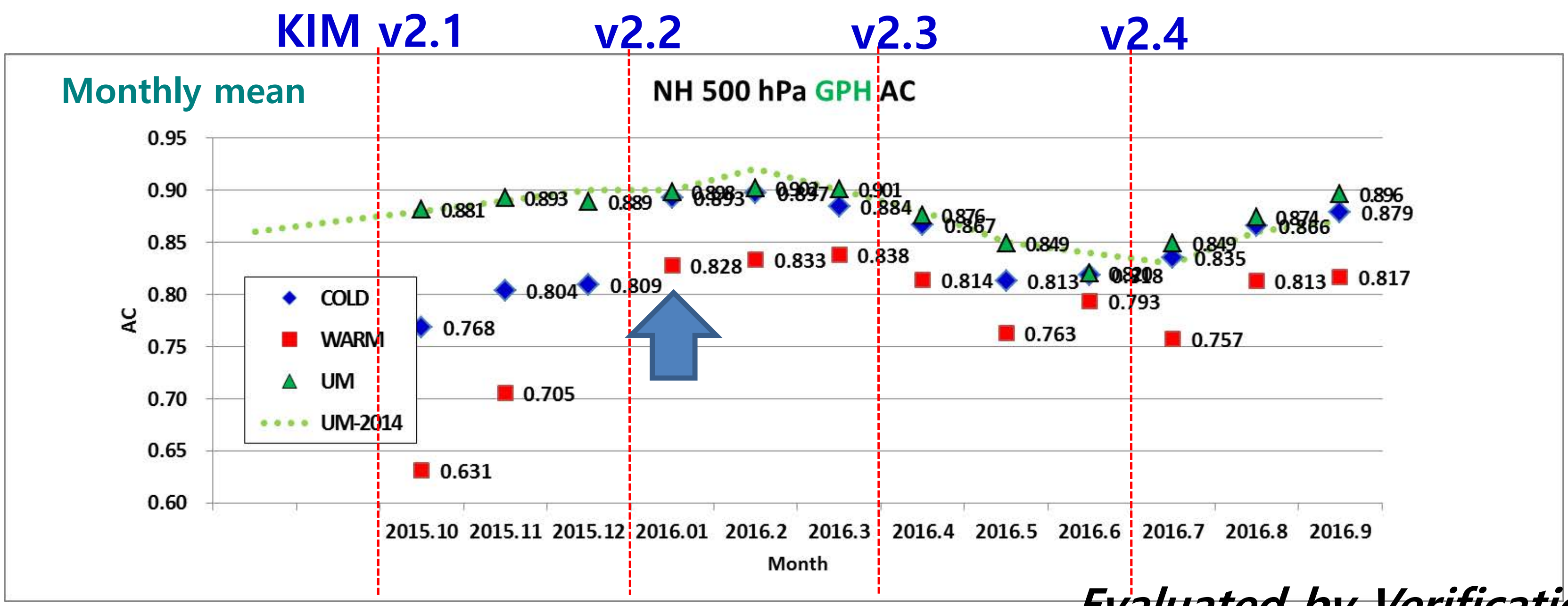
\- **Spectral transform** as the horizontal Filter

: Direct transform **from cubed sphere grid to wave space**

\- The observation data assimilated so far

Sonde, Surface, Aircraft, AMSU-A, IASI, GPO-RO, AMV, ATMS, CrIS, MHS, CSR, ScatWind (12 types)

- **Results of 3DVAR system**

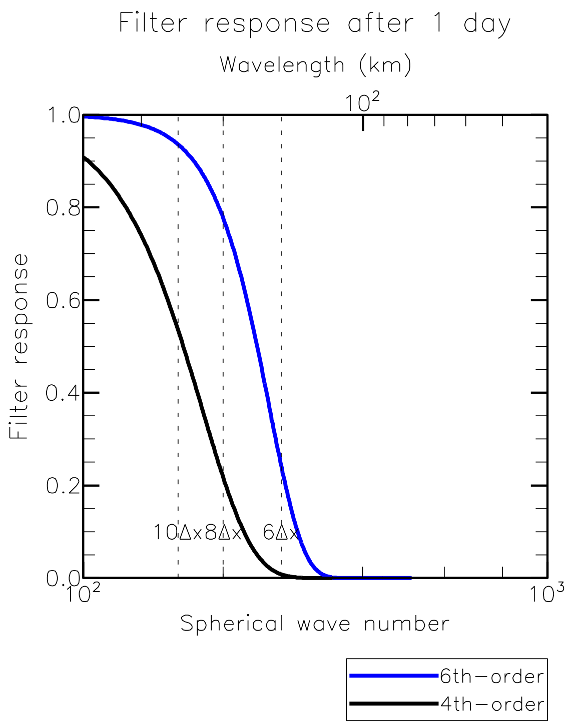


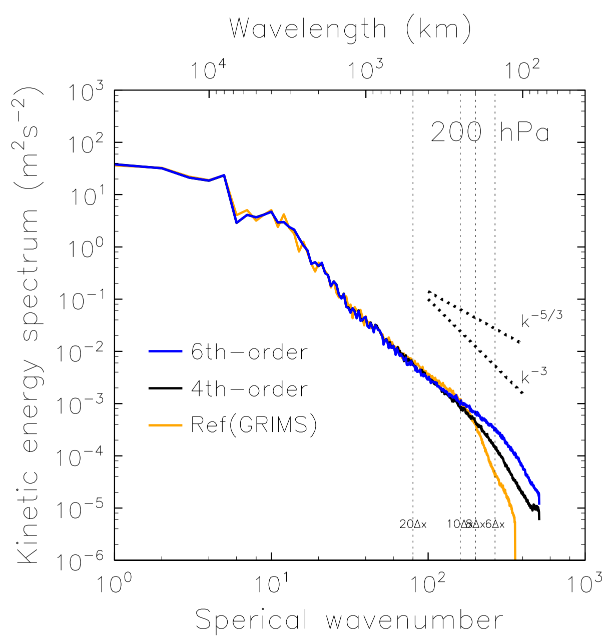
Evaluated by Verification Tea

Increase the order of the diffusion operator

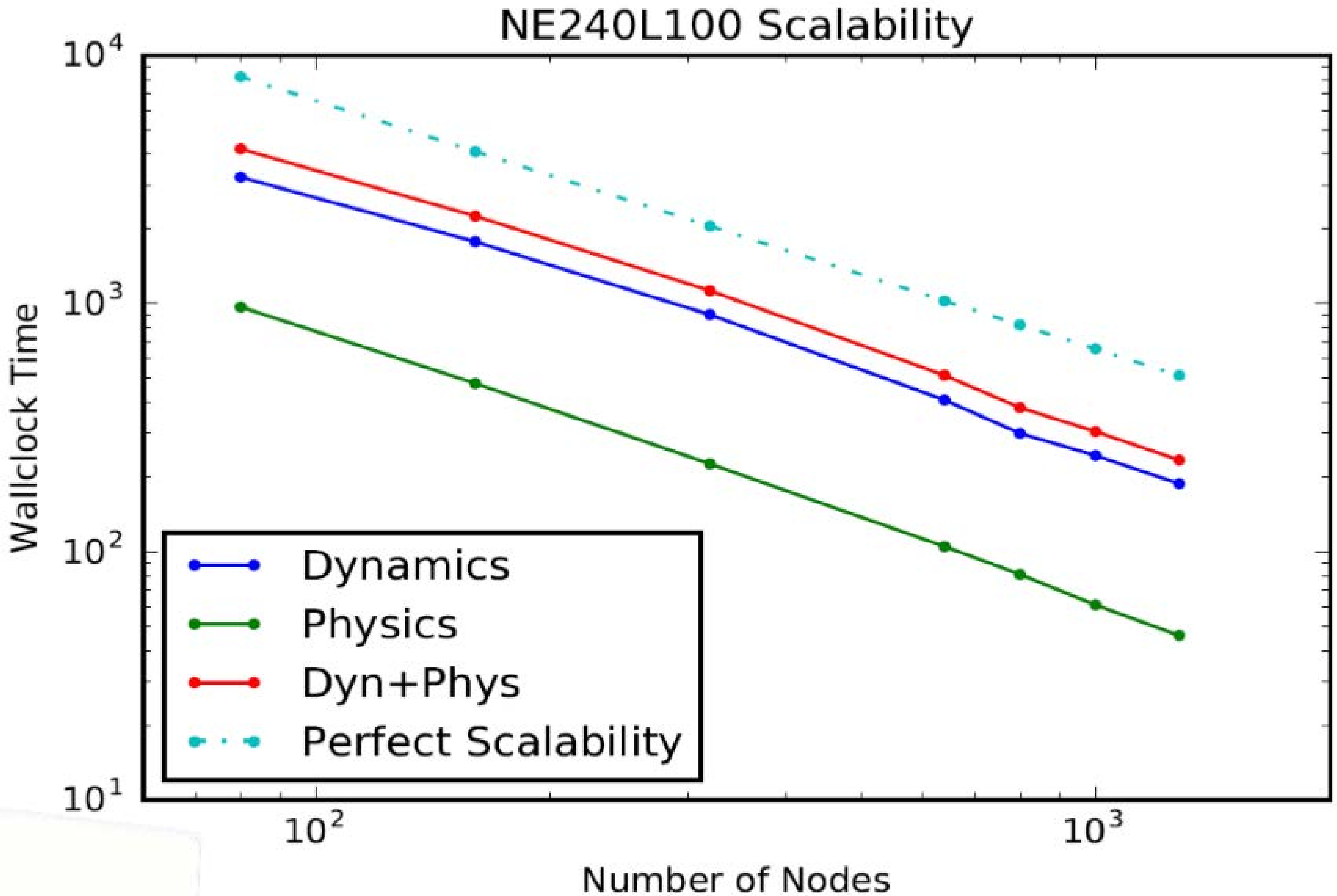
- The fourth-order diffusion scheme → sixth-order diffusion
- Outer loop time-split horizontal diffusion (5 times per a time-march)
- Increased dt and enhanced energy spectra are achieved.

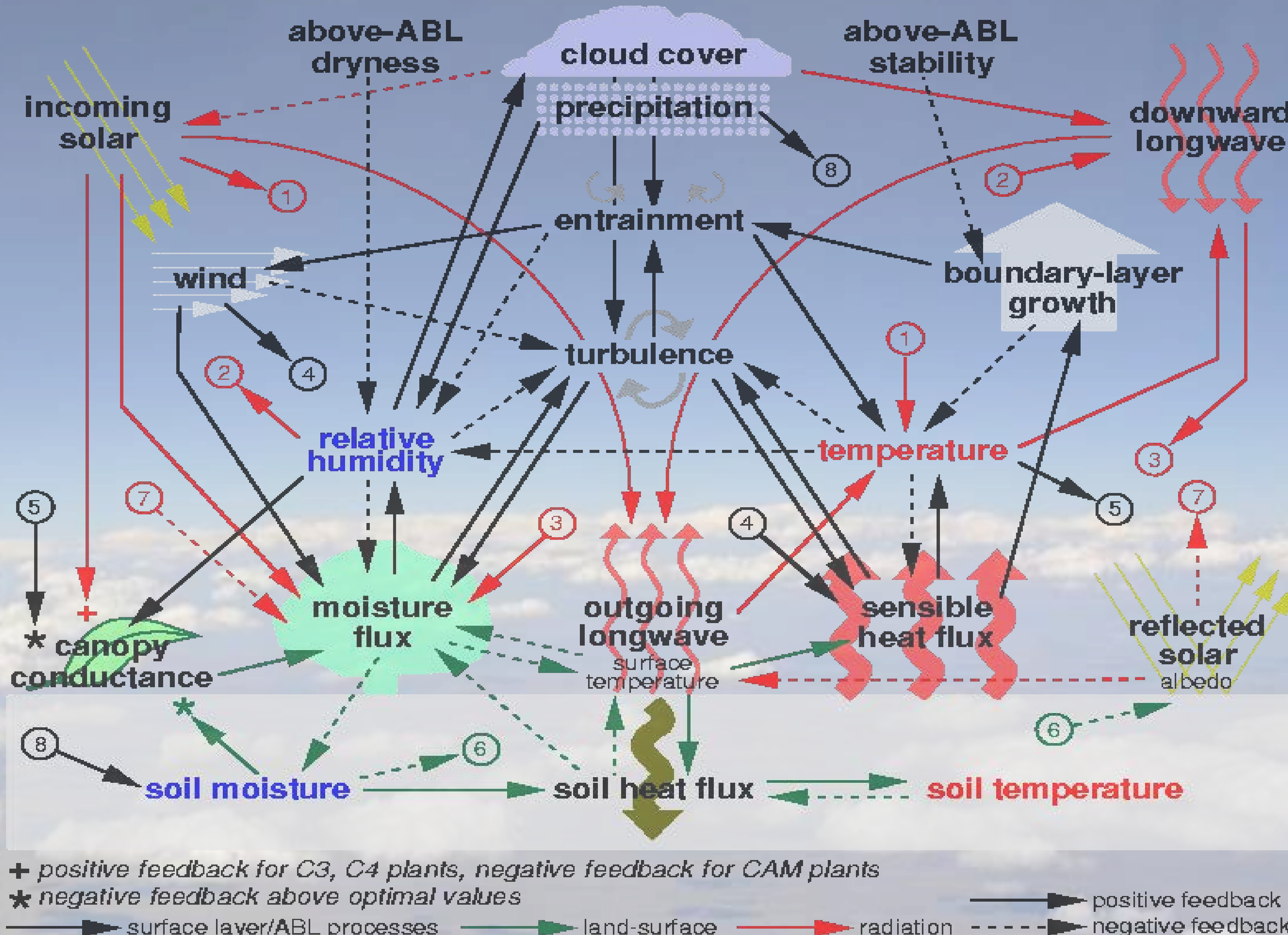
ne120	KIM2.2(CTL)	KIM2.3
dt	15	**60**
Diffusion order	2	**3**
Diffusion Coeff.	1.8E13	**3.0D21**





The results of KIM scalability test



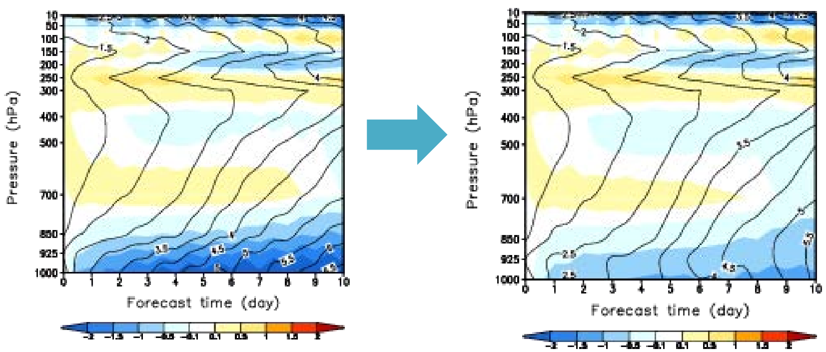


above-ABL dryness
cloud cover
above-ABL stability
incoming solar
precipitation
downward longwave
entrainment
wind
boundary-layer growth
turbulence
relative humidity
temperature
moisture flux
outgoing longwave
surface temperature
sensible heat flux
reflected solar
albedo
canopy conductance
soil moisture
soil heat flux
soil temperature
+ positive feedback for C3, C4 plants, negative feedback for CAM plants
★ negative feedback above optimal values
surface layer/ABL processes
land-surface
radiation
positive feedback
negative feedback

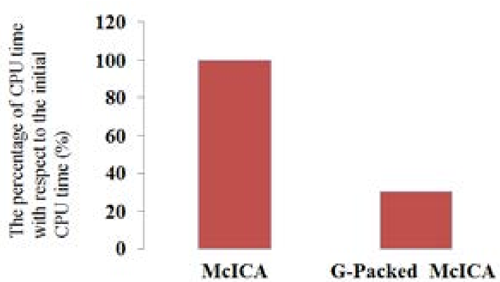
RAD

- Reducing cold bias at surface from snow albedo correction
- G-Packed McICA : 3 times faster than McICA without losing accuracy
- Tuned two-stream approximation : reduces RMS error to 60 % with no significant computational cost

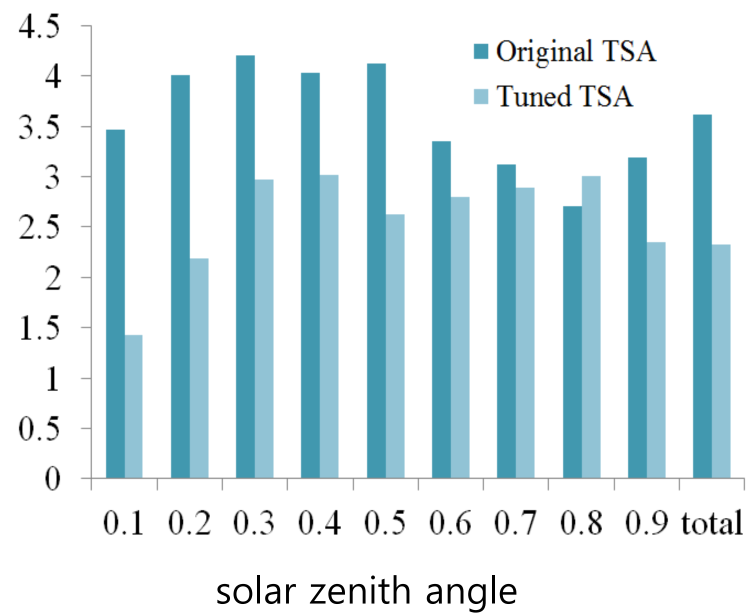
Improvement of clod bias at lower level by modification of snow albedo



Reducing computation time of McICA



RMS error of each cosine of solar zenith angle $\mu_0$bin



GWD-PBL

Scale-aware subgrid-scale orographic parameterization

- Scale separation of subgrid orography (meso/turbulent scales)
- Inclusion of turbulent scale orographic drag
- Improvement of mesoscale orographic drag

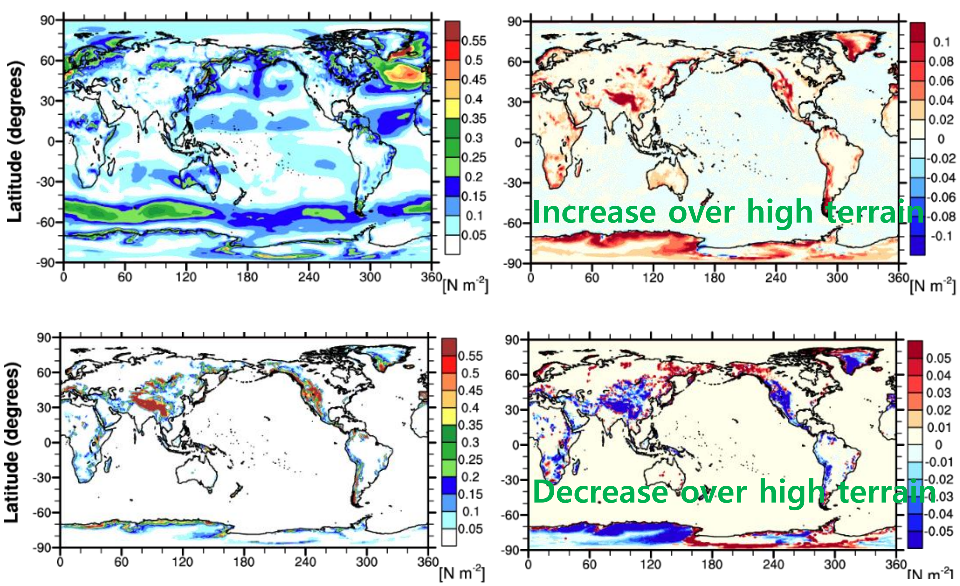
σ_f: standard deviation of turbulent scale orography
z_0: effective roughness length
z_1: lowest model-layer height

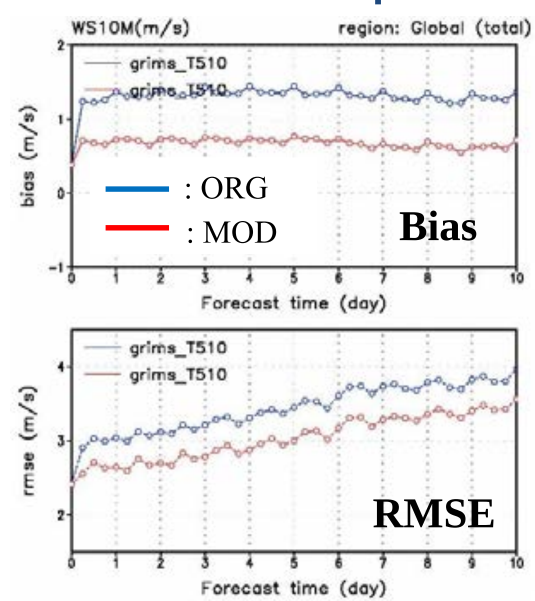
	Original (ORG)	**Modified (MOD)**
Turbulent scale orographic drag (SFC/PBL)		1 – 4km **$z_0 = \min(0.001\sigma_f, z_1)$ when $\sigma_f > 1$ m**
Mesoscale orographic drag (Orographic GWD)	1 km – Δx	4 km – Δx **Modified flow blocking drag**

ORG | **MOD-ORG** | **10-m wind speed**

Turbulent stress

Orographic stress



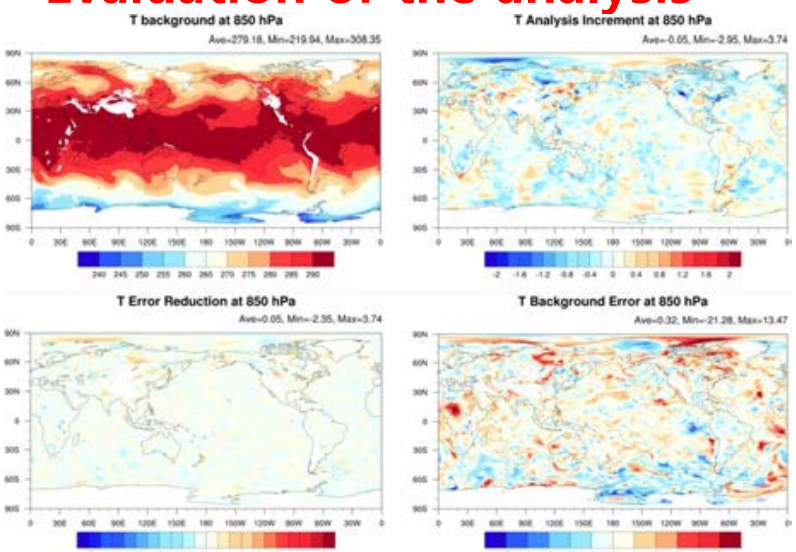


← **Improvement in 10-m wind speed error in terms of global average for a boreal winter (2016 January)**

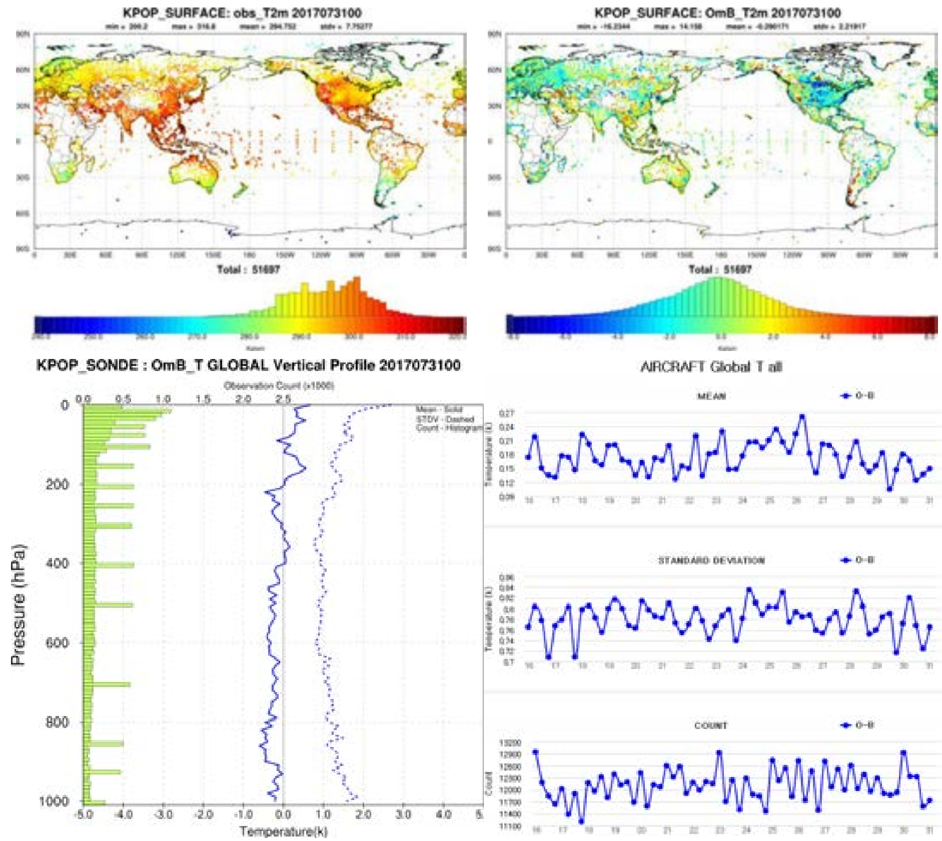
Data assimilation monitory system

- **Number of observation**

- **Evaluation of the analysis**



- **Conventional observation**

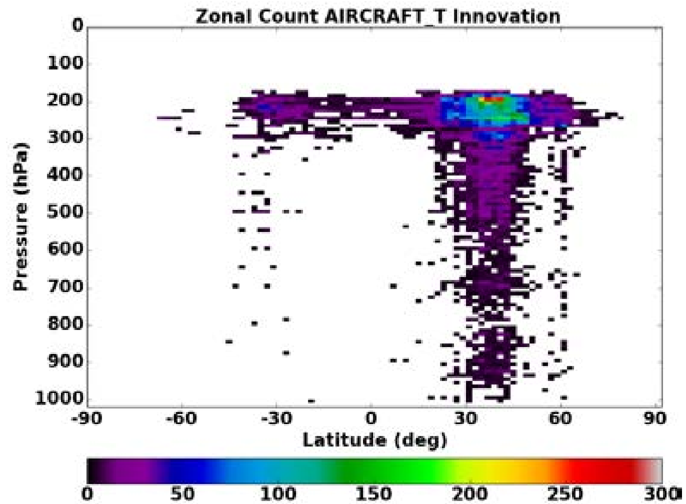


Aircraft Thinning update

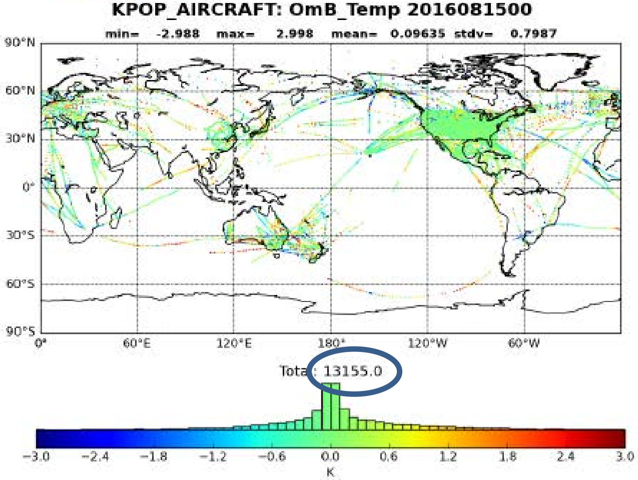
Previous version: 2D thinning boxes
(one for each column)

New version: 3D thinning boxes
(1 for each box)

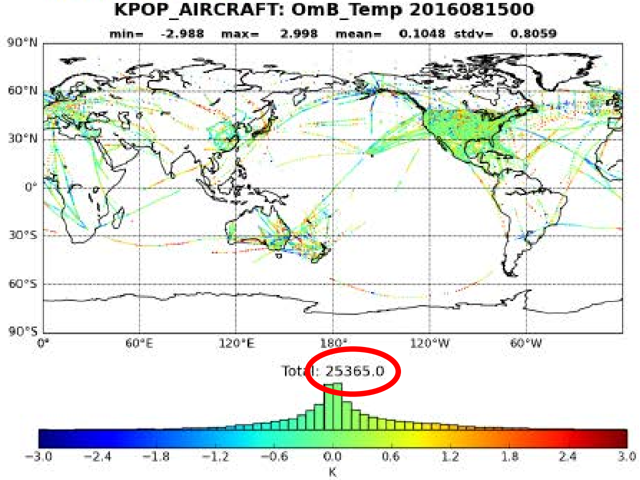
- 12 vertical ranges from 11 mandatory levels (hPa)
  1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100



Old (r333)



New (r334)



- **Number of observation**

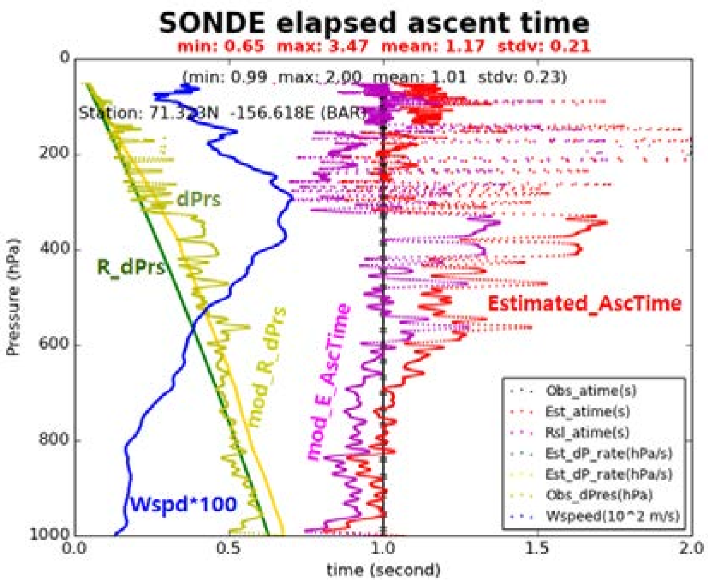
  13155 → 25365 (~93% inc.)

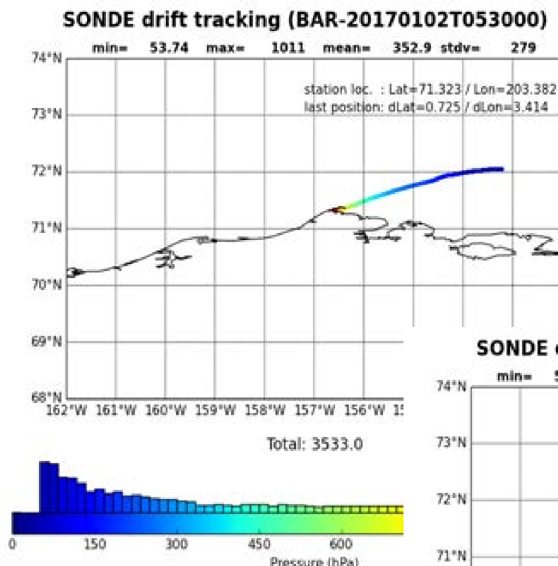
  but, not much diff. in statistics

Almost 2 times bigger observations

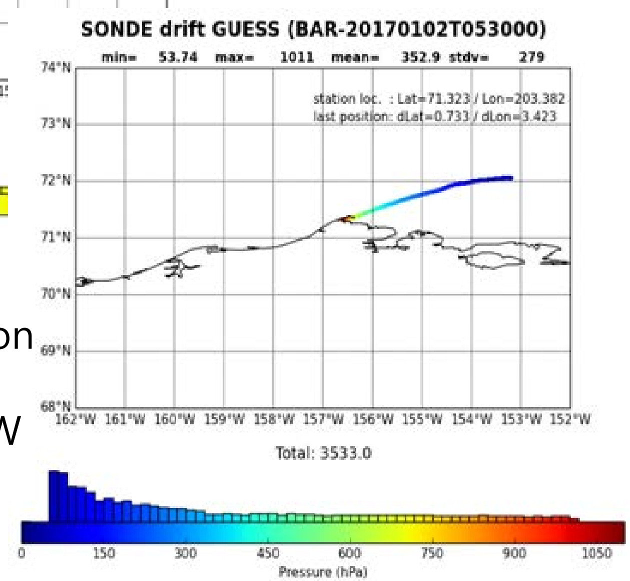
SONDE drift estimation in KPOP (Prototype for 1 point)

- **BAR (Barrow, AK, USA)**
  - 151 obs. used from Jan. to Aug. 2017 (~20 obs. at each month)





Station:
71.323N / 156.618W
Last location:
72.048N / 153.204W
Distance = 143.9 km



Balloon drift estimation
Last location:
72.056N / 153.195W
Distance = 144.7 km

- Balloon drift estimation model in KPOP
  - calculate correlations between observation variables
  - regression model: rate of d_Prs & $Wspd$ weighting

  → elapsed ascent time estimation

$$x_k = x_{k-1} + \frac{t_k(u_k + u_{k-1})/2}{d_{ref} \times \cos(\emptyset)}$$ -(Longitude in deg.)

$$y_k = y_{k-1} + \frac{t_k(v_k + v_{k-1})/2}{d_{ref}}$$ -(Latitude in deg.)

where,

$$t_k = \Delta Prs / (\overline{R_{dP}} + \overline{R_{dP}} \times E_{Ws})$$ -(ascent time in sec.)

$$\overline{R_{dP}} = [(p_a \times Prs_k^2 + p_b \times Prs_k + p_c) + (p_a \times Prs_{k-1}^2 + p_b \times Prs_{k-1} + p_c)]/2$$

$$\Delta Prs = Prs_{k-1} - Prs_k$$

$$E_{Ws} = w_a \times W_{spd} + w_b$$

Location error: 0.008 (lat) & 0.009 (lon)
= **0.942 km** (vs. 143.9 km)
➔ **99.3% error reduction**

Horizontal localization for LETKF

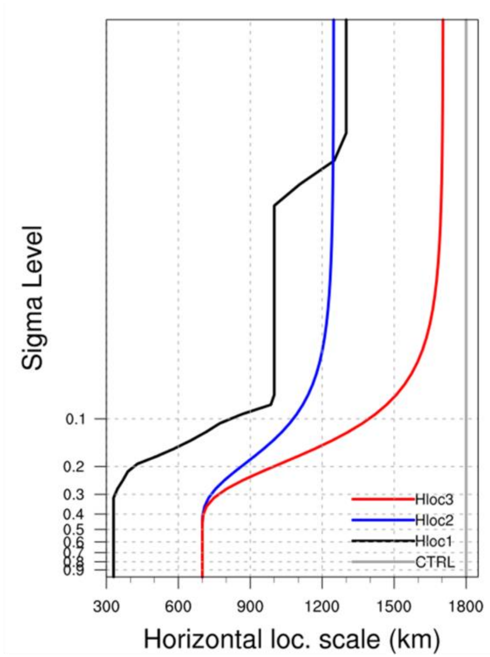


Fig 6. **CTRL** is constant horizontal localization scale, which is used in the original KIAPS-LETKF system (gray line). **Hloc1** is GSI's localization scale (black line), **Hloc2** and **Hloc3** are modified localization scale (blue and red line).

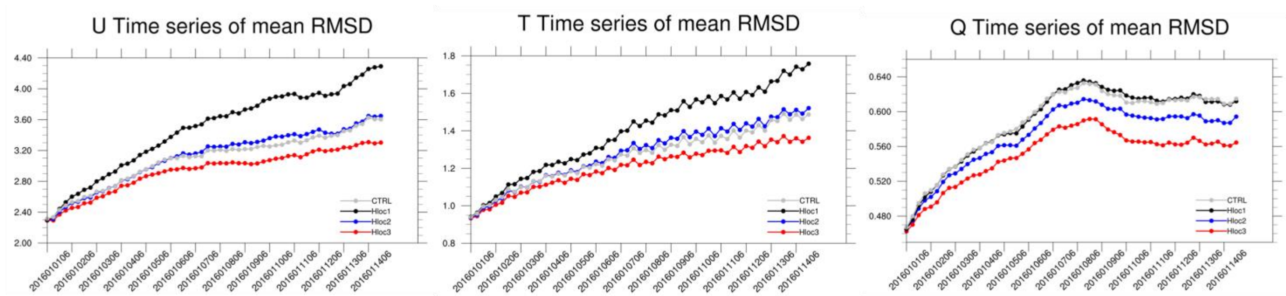


Fig 7. **Time series of global mean RMSD** against IFS analysis data over 10~1000hPa. It shows **Hloc3** is the best performance in this study.

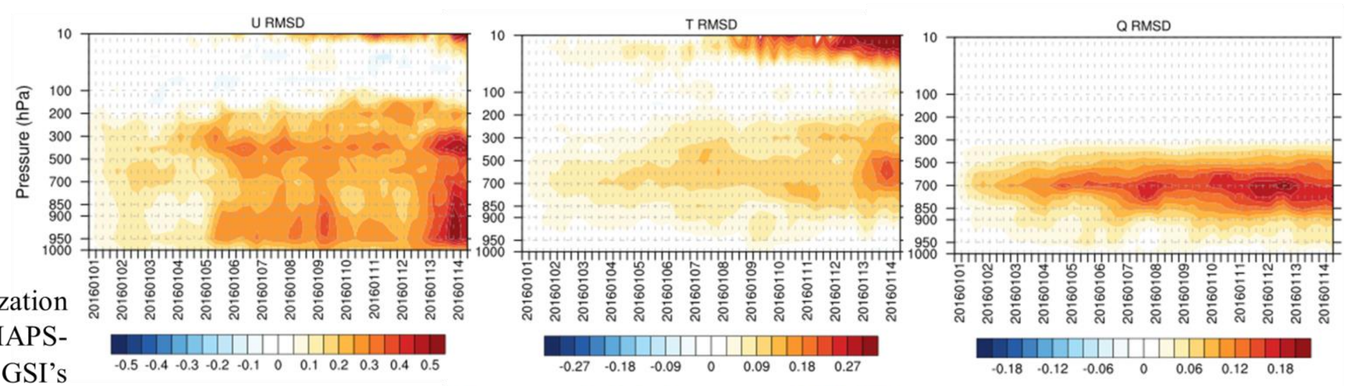
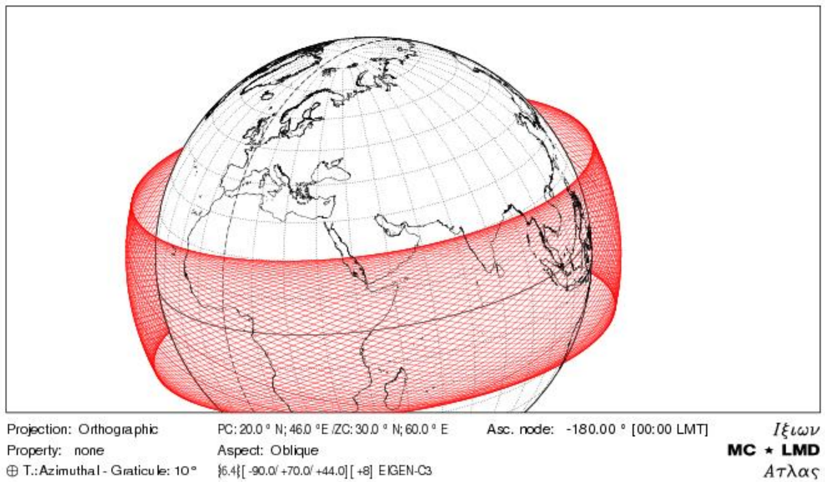
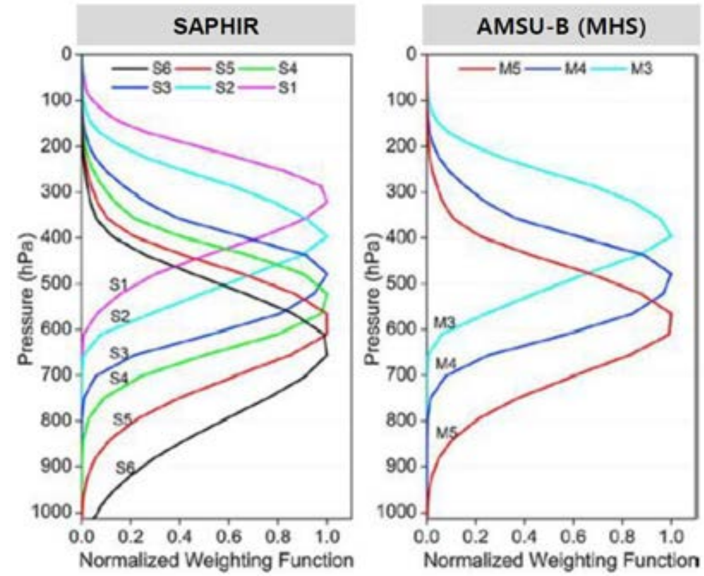


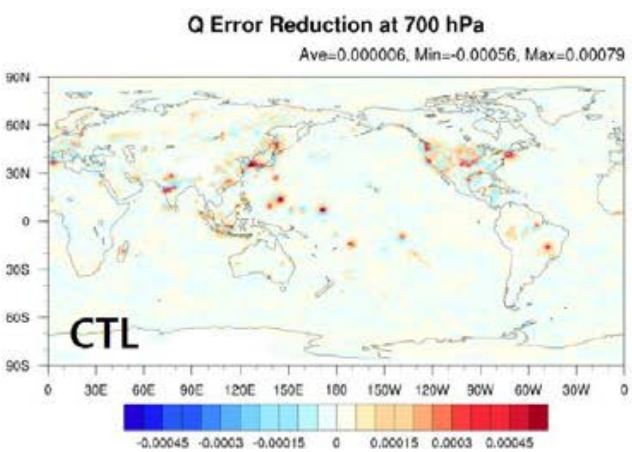
Fig 8. **Time series of difference of global averaged RMSD** between CTRL and Hloc3. All the variables improve over troposphere.

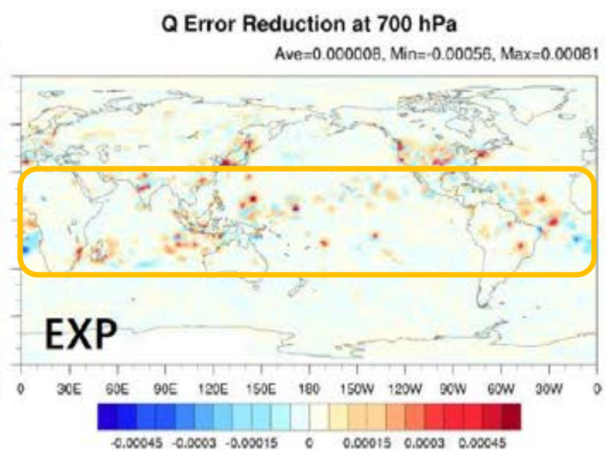
Megha-Tropiques **SAPHIR**: microwave humidity sounder

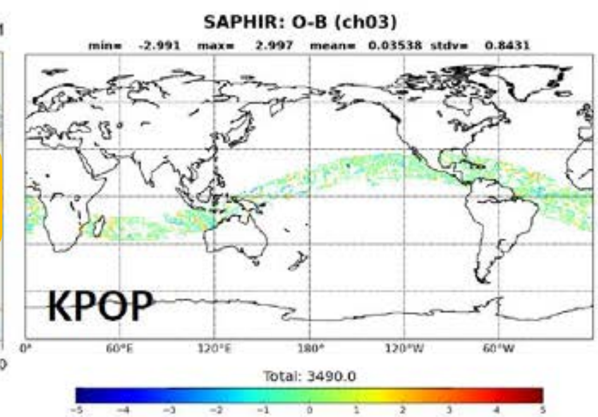




CTRL: Conventional, GPS-RO, AMV, ScatWind, AMSUA
EXP : CTRL + SAPHIR 6 channels

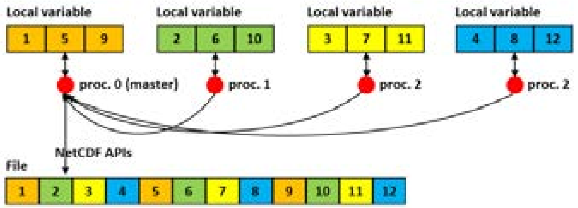






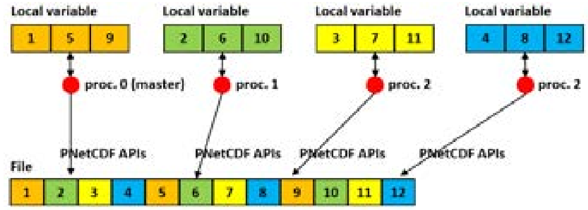
Improvement of I/O performance FRAME

sequential I/O



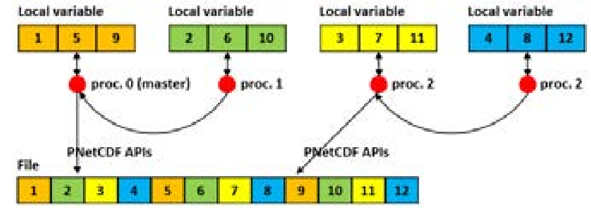
- The master process collects all the data and outputs it.
- Using NetCDF APIs

parallel I/O



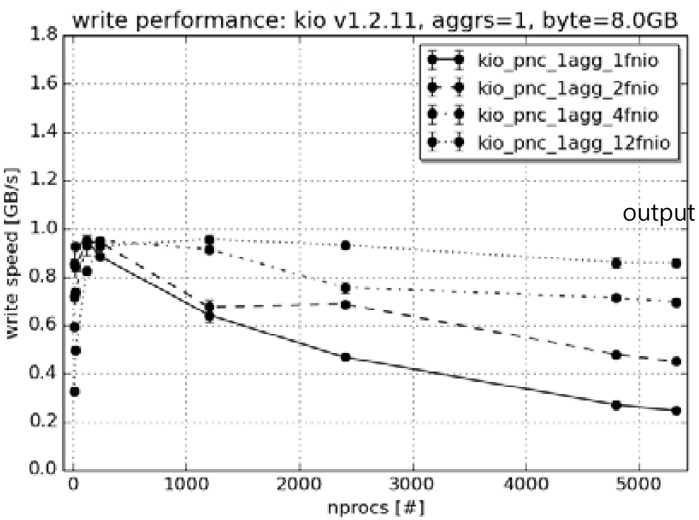
- All processes access and write the file at the same time.
- Using PNetCDF APIs

I/O decomposition



- Only some processes participate in the output. (output processes)
- Using PNetCDF APIs (only output processes)

@Nuri



output procs	I/O speed
444,	0.86 GB/s (x **3.5**)
1332,	0.70 GB/s
2664,	0.45 GB/s
5328,	0.25 GB/s

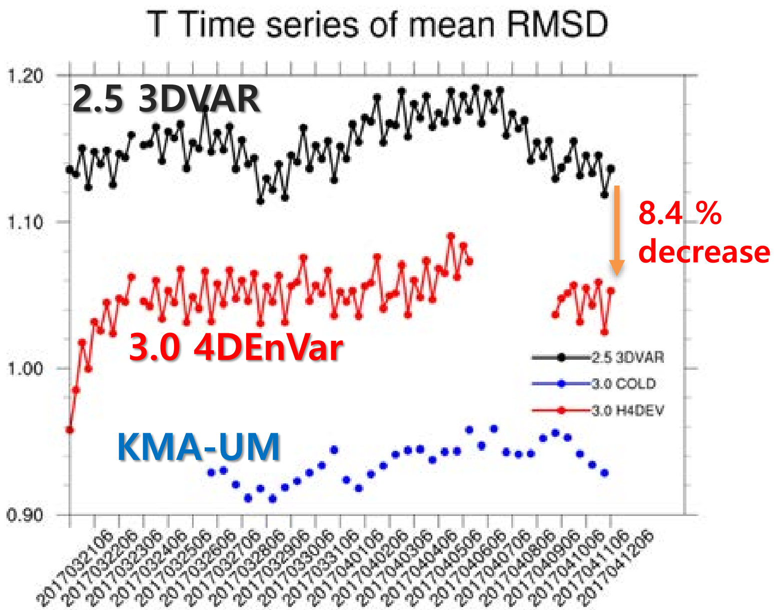
- The # of output processes is set to x1, x1/2, x1/4, x1/12 of the # of total processes.
- With 5,328 processes, it is 3.5 times faster to use 444 processes than to use the entire processes for output.

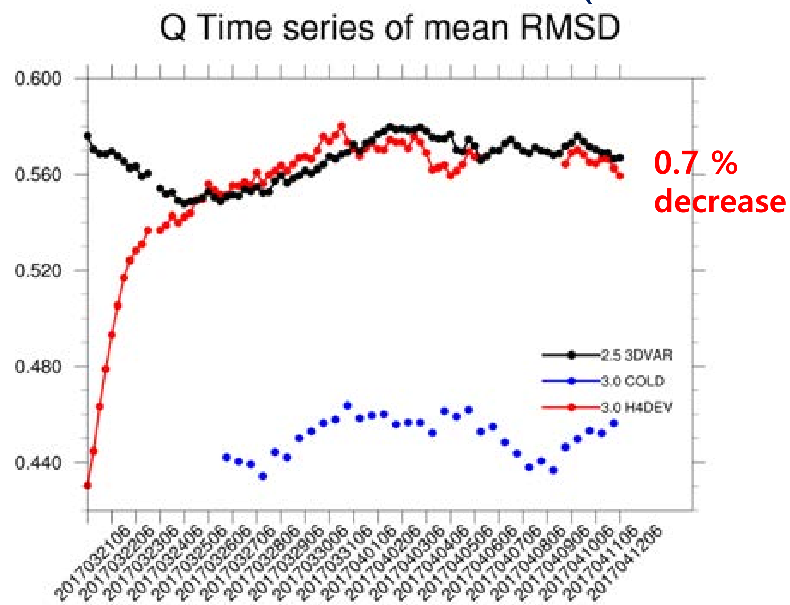
	w/o I/O decomp.	w/ I/O decompo.	speed-up
ncores	10,008		
nios	5,004	139	
total (sec)	14,259 (3h 58m)	12,244 (3h 24m)	**1.16**
write (sec)	1,318 (9.2%)	478 (3.9%)	**2.76**

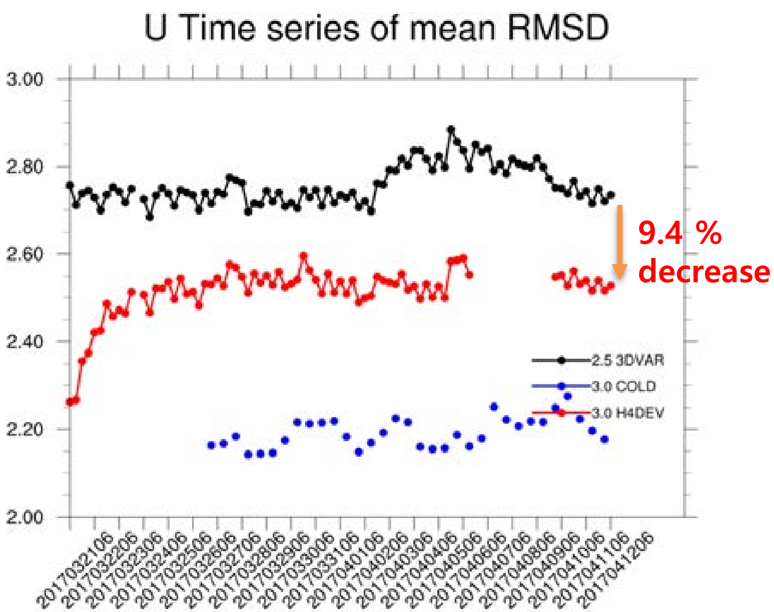
- When applied to KIM, the performance is improved about 2.76 times in the output and about 1.16 times in the total when compared to the conventional parallel output.

Analysis RMSD against IFS analysis

Calculated between (**10~1000hPa**)







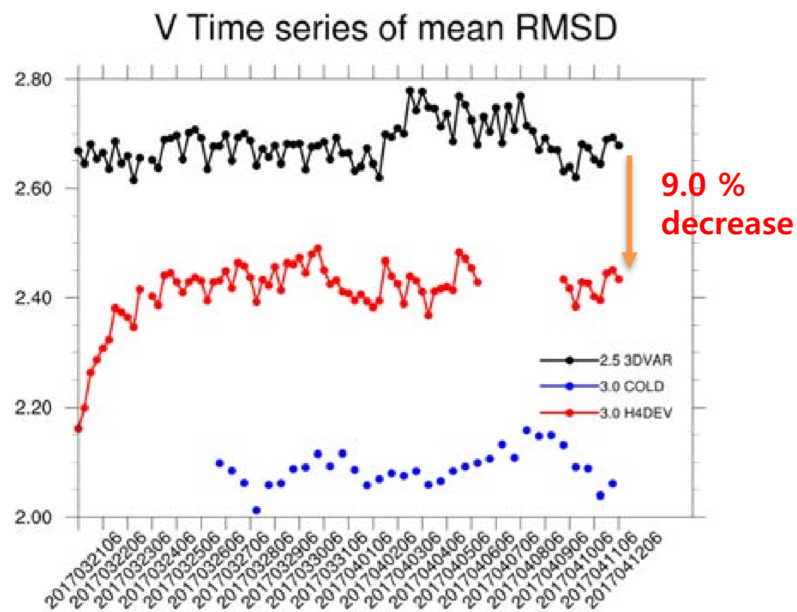
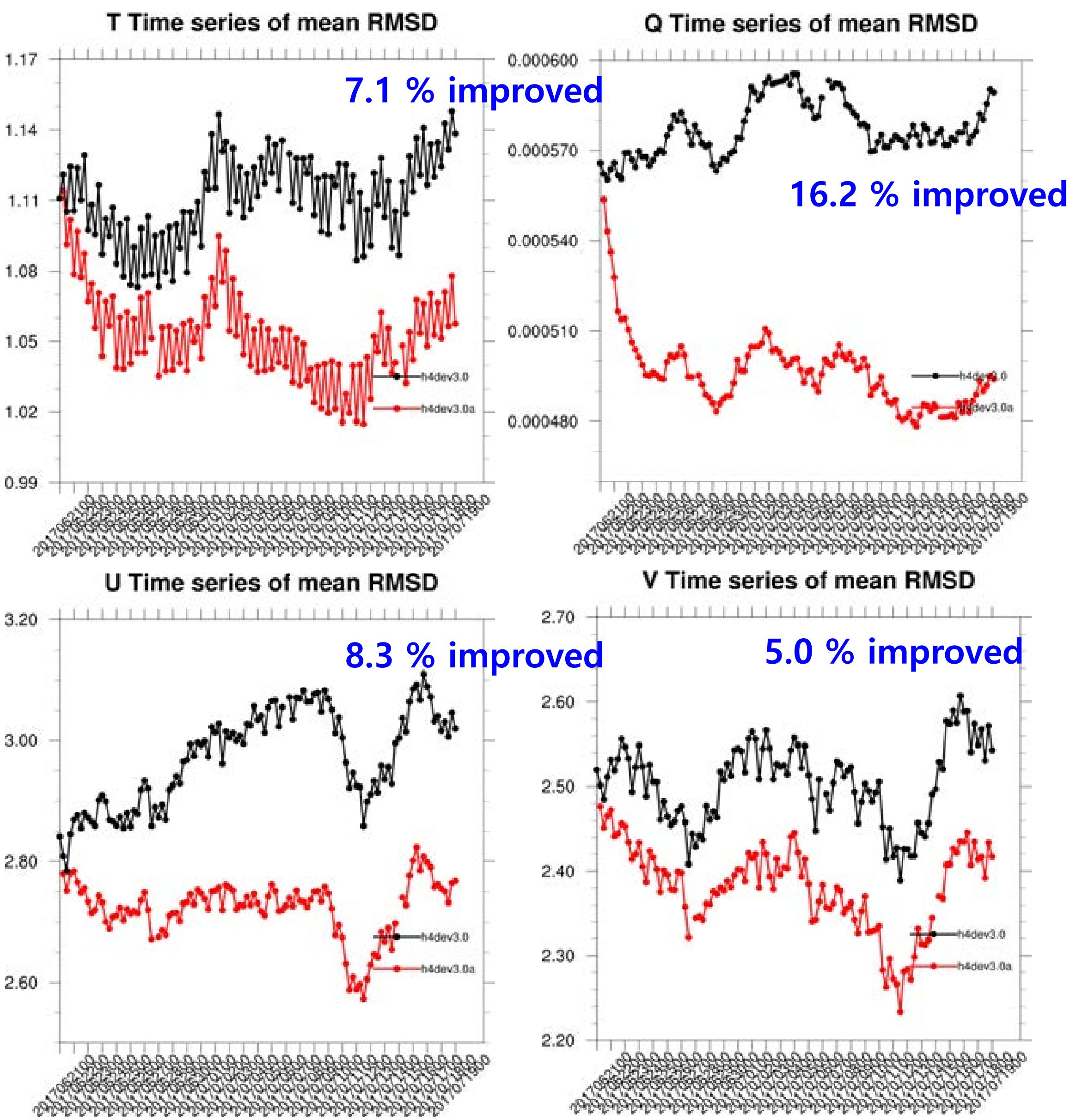


Table of KIAPS DA updates

	KIM3.0.01	KIM3.0a
KPOP	• **Bug fixed** (Surface height correction for 2 m temperature and moisture) • **Remove Land data from CrIS** • **4D Thinning except for Surface and ScatWind**	• **LEOGEO satellite for AMV** • **For MHS: land usage and obs error reduction** • **Bug fixed** (Equidistance thinning box) • **4D Thinning except for Surface**
DA Technique	**Hybrid-4DEnVar** • **Reduce a static background error of q** : Rescale factor of q: 3 → 1 : Ensemble background error works more • Inflation of observation error **Surface** x 2, **CrIS** x 2, **Aircraft** x 1.3, **AMV** x1.3, **IASI** x1.3 • Add observation: COMS-CSR	**Hybrid-4DEnVar** • **Bug fix on reading ensemble samples** • Ratio of ensemble background error: 30% • **Recentering for Q** : Var 50 % and Ensemble mean 50 % for q : Bug fix on q initialization • **Pseudo-RH** Inflation of observation error **ScatWind** x 1.3
	LETKF • Add Observation : **MHS**, **CrIS**, **ATMS**, and **COMS-CSR** • Modification of additive inflation : Inflation factor (0.1 → 0.3) ~~• Modification of horizontal localization~~ ~~: Varies with level increasing~~ (GSU's localization profile was referred) • Modification of vertical localization for : Weighting function from KPOP	**LETKF** • Add Observation : **MHS**, **CrIS**, **ATMS**, and **COMS-CSR** • Modification of additive inflation : Inflation factor (0.1 → 0.3) • **Modification of horizontal localization** : Varies with level increasing (Min: 700 km, Max: 1800 km) • Modification of vertical localization for radiance : Weighting function from KPOP

+ KIM3.0a model update

Evaluation of the KIM analysis



H4DEV3.0

H4DEV3.0a

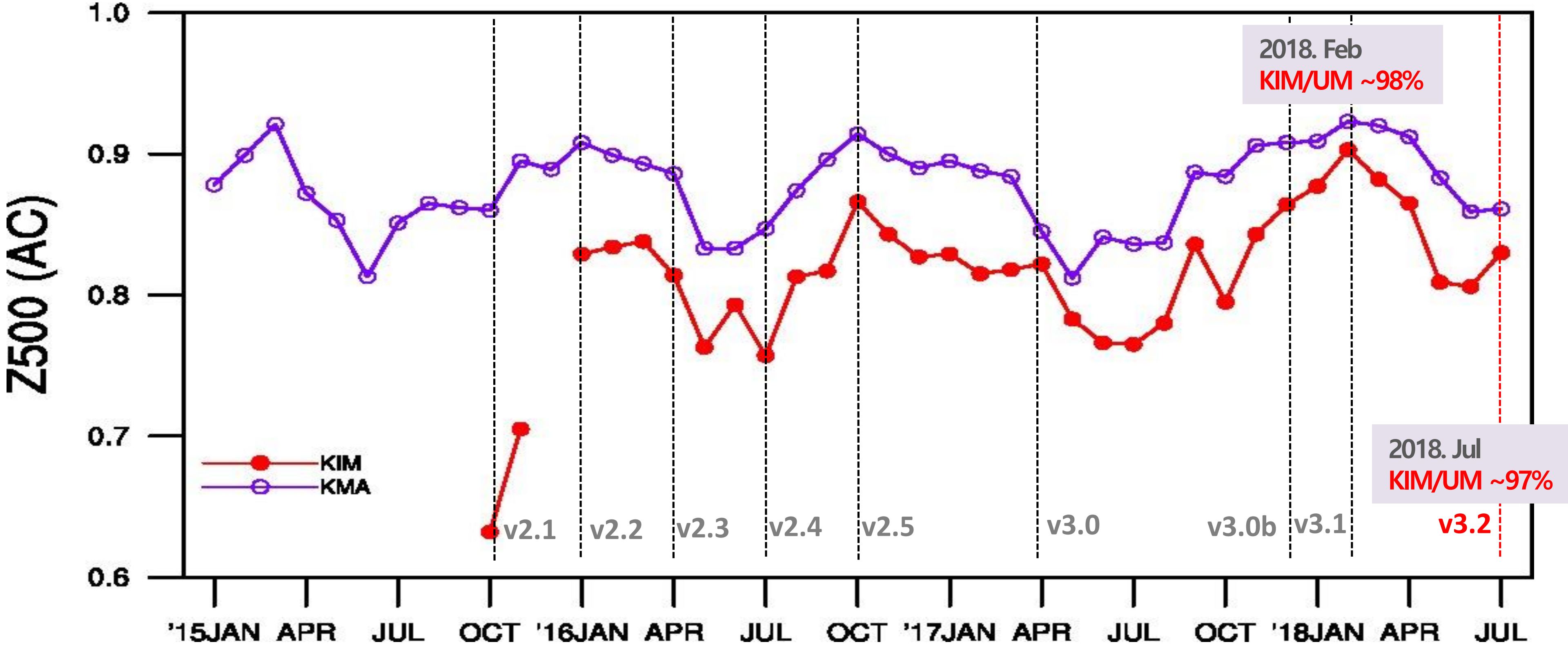
- H4DEV3.0a is better, especially in Q

- H4DEV3.0a:
  4DEnVar update
  KPOP update and LEOGEO
  KIM model update

KIM Real time forecasts skill

500hPa geopotential height anomaly correlation at t=+120h fcst

KMA UM vs KIM



Lower order basis function (np4 → np3)

The reduction in accuracy due to the use of the lower order basis function seems to be small in NWP.
But, larger time-step size can be allowed in the model → Enhancement of calculation efficiency