Overview of the KIAPS’s next generation global model
KIM (Korean Integrated Model)

Young C. Kwon
Korea Institute of Atmospheric Prediction Systems (KIAPS)

Contents

- overview of KIAPS
- dynamic core
- physics
- data assimilation
- model framework and verification results
- summary
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: 2 divisions, 6 teams, 2 offices
- 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:
6th 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

[Graph showing NE240L100 Scalability with different lines labeled Dynamics, Physics, Dyn+Phys, and Perfect Scalability. The y-axis is logarithmic for Wallclock Time, ranging from 10^1 to 10^4, and the x-axis is logarithmic for Number of Nodes, ranging from 10^2 to 10^3.]
Development of Non-hydrostatic Dyn. (DCMIP)

Baroclinic instability, \( Ps \) (9-days)

- Idealized tropical cyclone with simplified physical forcings

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

https://www.earthsystemcog.org/projects/dcmip-2012/Test_Cases/results_by_model
Algorithmic Change
EP-based $\rightarrow$ UP_based

- 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
<table>
<thead>
<tr>
<th>Scheme</th>
<th>Updated</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation (복사)</td>
<td>• unified RRTMG</td>
<td>Iacono et al. 2008</td>
</tr>
<tr>
<td>Revised RAD (RRTMK)</td>
<td>• reduced MCICA</td>
<td>Beak 2017</td>
</tr>
<tr>
<td></td>
<td>• updated ancillaries (aerosol, GMAO ozone, reflectivity, emissivity, snow albedo)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Improved two-stream approximation for shortwave radiation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Scale-awareness for sub-grid hydrometeors</td>
<td></td>
</tr>
<tr>
<td>Land surface (지면)</td>
<td>• 3-layer sea-ice model</td>
<td>Ek et al. 2003</td>
</tr>
<tr>
<td>Revised LSM</td>
<td>• frozen processes (20, conductivity over snow cover, flux over sea-ice)</td>
<td>Koo et al. 2016</td>
</tr>
<tr>
<td></td>
<td>• USGS to IGBP for land data</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• soil moisture initialization</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• consistent diffusivity in LSM and RAD</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Heterogeneous land-surface parametrization</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Roughness length considering snow dives</td>
<td></td>
</tr>
<tr>
<td>Ocean surface layer (해수면)</td>
<td>Diurnal SST OSH</td>
<td>Kim and Hong 2010</td>
</tr>
<tr>
<td></td>
<td>• SST warming effect</td>
<td>Lee and Hong 2017</td>
</tr>
<tr>
<td></td>
<td>• Considering salinity effect</td>
<td></td>
</tr>
<tr>
<td>Boundary layer (경계층)</td>
<td>Scale-aware non-local PBL</td>
<td>Hong et al. 2006</td>
</tr>
<tr>
<td></td>
<td>• top-down mixing</td>
<td>Shin and Hong 2015</td>
</tr>
<tr>
<td></td>
<td>• updated background diffusion &amp; heating rate</td>
<td>Lee et al. 2016</td>
</tr>
<tr>
<td>Gravity wave drag (중력파)</td>
<td>Sub-grid orographic GWD</td>
<td>Hong et al., 2008</td>
</tr>
<tr>
<td></td>
<td>• flow blocking drag</td>
<td>Choi and Hong 2015</td>
</tr>
<tr>
<td></td>
<td>• orographic anisotropy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• updated efficiency/intermittency factor</td>
<td></td>
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<tr>
<td></td>
<td>Non-orographic GWD</td>
<td>Choi et al. 2017</td>
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<tr>
<td>Deep convection (깊은대류)</td>
<td>Scale-aware mass-flux CPS</td>
<td>Han and Pan 2011</td>
</tr>
<tr>
<td></td>
<td>• revised autoconversion &amp; entrainment rate</td>
<td>Lim et al. 2014</td>
</tr>
<tr>
<td></td>
<td>• moisture-based trigger threshold</td>
<td>Han et al. 2016</td>
</tr>
<tr>
<td></td>
<td>• scale-aware / aerosol-aware</td>
<td>Kwon and Hong 2016</td>
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<tr>
<td>Shallow convection (얕은대류)</td>
<td>Adjustment SCV</td>
<td>Hong et al. 2013</td>
</tr>
<tr>
<td></td>
<td>• improved eddy diffusivity profile (2.5)</td>
<td></td>
</tr>
<tr>
<td>Microphysics (미세물리)</td>
<td>WSM5 MPS</td>
<td>Hong et al. 2004</td>
</tr>
<tr>
<td></td>
<td>• effective radius</td>
<td>Bae et al. 2016</td>
</tr>
<tr>
<td>Cloudiness (운량)</td>
<td>Prognostic CLD</td>
<td>Park et al. 2016</td>
</tr>
<tr>
<td></td>
<td>• revised CPS condensate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• consistency (cloud-MPS-CPS-RAD)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• reduced high cloud fraction at high latitude</td>
<td></td>
</tr>
</tbody>
</table>
The grid-size dependency is considered (scale-aware scheme)

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

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

Adapted from Hong and Pan (1998, MWR)

- Cloud-base mass flux \( \propto (1 - \sigma)^2 \)
- Convective Inhibition \( \propto (1-\sigma) \)
- Moisture detrained to grid scale \( \propto \sigma \)

### 24-h accumulated precipitation

<table>
<thead>
<tr>
<th>( \Delta x )</th>
<th>( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 km</td>
<td>0.1</td>
</tr>
<tr>
<td>5 km</td>
<td>0.5</td>
</tr>
<tr>
<td>1 km</td>
<td>0.9</td>
</tr>
</tbody>
</table>

- No CPS in the domain with \( \Delta x = 3 \text{ km} \)
- Modified SAS in the domain with \( \Delta x = 3 \text{ km} \)
- Original SAS in the domain with \( \Delta x = 3 \text{ km} \)
Evaporation over Ocean

- To apply the saturated vapor pressure for seawater over ocean
  Global sea surface salinity $\sim 32$-38‰

Improvement of light rain forecasting

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

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

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 Infrared 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 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**

![Graph showing Monthly mean of KIM v2.1, v2.2, v2.3, v2.4 for NH 500 hPa GPH AC from 2015.10 to 2016.9]

Evaluated by Verification Team
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

Main code written by Python

Application
- Configuration
- Flow control
- IO
- MPI parallel
- pre/post processing

PyMIP (allocation, compiling, import, call)

Low-level code for mass computation

Fortran C OpenCL ISPC CUDA

Processor Hardware

CPU
AMD GPU NVIDIA GPU
Intel MIC
FPGA
General Bilinear Interpolation between Spherical Grids

Generalized bilinear interpolation

(a) Quadrangular

(b) Irregular

Remapping between arbitrary spherical grids

Fast and scalable search algorithm

![Graph showing scalability of search algorithm](image)

- $N^2$
- $N \log N$
- $N$
- Exp
Improvement of I/O performance using I/O decomposition method

- The master process collects all the data and outputs it.
- Using NetCDF APIs
- All processes access and write the file at the same time.
- Using PNetCDF APIs
- Only some processes participate in the output. (output processes)
- Using PNetCDF APIs (only output processes)

**@Nuri**

write performance: kio v1.2.11, aggrs=1, byte=8.0GB

- **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

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<th></th>
<th>w/o I/O decom.</th>
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<th>speed-up</th>
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<td>ncores</td>
<td>10,008</td>
<td>139</td>
<td>1.16</td>
</tr>
<tr>
<td>nios</td>
<td>5,004</td>
<td>1,318 (9.2%)</td>
<td>2.76</td>
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- 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
Thank you
Parallel design for local implicit diffusion

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

2. Convert index coordinates

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
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

![Graph showing monthly mean NH 500 hPa GPH AC for KIM v2.1 to v2.4]
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.

<table>
<thead>
<tr>
<th>ne120</th>
<th>KIM2.2(CTL)</th>
<th>KIM2.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>dt</td>
<td>15</td>
<td>60</td>
</tr>
<tr>
<td>Diffusion order</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Diffusion Coeff.</td>
<td>1.8E13</td>
<td>3.0D21</td>
</tr>
</tbody>
</table>

Filter response after 1 day

Wavelength (km)

![Filter response graph](image)

Wavelength (km)

Kinetic energy spectrum (m^2 s^-2)

Spherical wavenumber

- 6th-order
- 4th-order
- Ref(GRIMS)
The results of KIM scalability test

![Graph showing scalability results](image-url)
▪ 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 cold 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
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

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

<table>
<thead>
<tr>
<th></th>
<th>Original (ORG)</th>
<th>Modified (MOD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulent scale orographic drag</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(SFC/PBL)</td>
<td></td>
<td>$1 – 4\text{km}$</td>
</tr>
<tr>
<td>$z_0 = \min(0.001\sigma_f, z_1)$ when $\sigma_f &gt; 1 \text{ m}$</td>
<td>$4 \text{ km} – \Delta x$</td>
<td></td>
</tr>
<tr>
<td>Mesoscale orographic drag</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Orographic GWD)</td>
<td>$1 \text{ km} – \Delta x$</td>
<td>$4 \text{ km} – \Delta x$</td>
</tr>
</tbody>
</table>

10-m wind speed

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

Increase over high terrain
Decrease over high terrain
Data assimilation monitoring system

- Number of observation

- Conventional observation

- Evaluation of the analysis
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

- 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

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

**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)
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Analysis RMSD against IFS analysis

Calculated between (10~1000hPa)

T Time series of mean RMSD

Q Time series of mean RMSD

U Time series of mean RMSD

V Time series of mean RMSD

KMA-UM

8.4 % decrease

9.4 % decrease

0.7 % decrease

9.0 % decrease

2.5 3DVAR

3.0 4DEnVar

2.5 3DVAR

3.0 COLD

3.0 H4DEV

2.5 3DVAR

3.0 COLD

3.0 H4DEV

2.5 3DVAR

3.0 COLD

3.0 H4DEV

2.5 3DVAR

3.0 COLD

3.0 H4DEV
<table>
<thead>
<tr>
<th><strong>Table of KIAPS DA updates</strong></th>
<th>KIM3.0.01</th>
<th>KIM3.0a</th>
</tr>
</thead>
</table>
| **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 |
| **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 | **• 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 | • 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
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 $\rightarrow$ 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 $\rightarrow$ Enhancement of calculation efficiency