Km-scale NWP at JMA

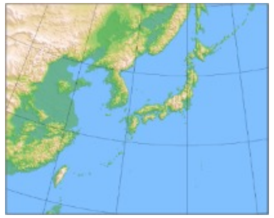
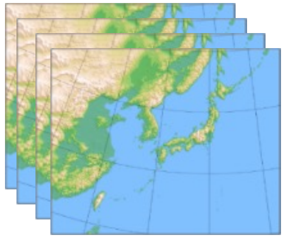
Numerical Prediction Division,
Japan Meteorological Agency

Km-scale NWP for MCS prediction at JMA

- Improving mesoscale convective systems (MCS) prediction : one of the important targets for the JMA's NWP systems
  - As stated in the JMA NWP strategic plan https://www.jma.go.jp/jma/en/Activities/nwp.html
  - Disasters caused by heavy rains due to MCSs occur almost every year in Japan and tend to be more serious recently. Contribution to disaster mitigation is one of the missions of JMA. NWP systems play important roles
- This presentation reports recent activities and deliverables of JMA's NWP R&D for better MCS prediction

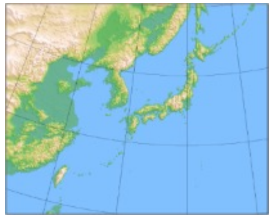
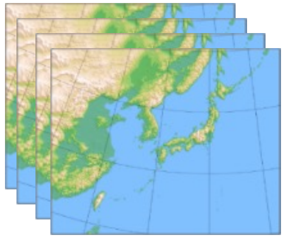
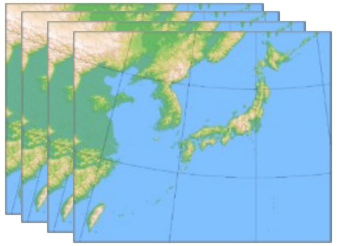
Operational regional NWP models at JMA

as of October 2025

	Local Forecast Model (LFM)	Meso-scale Model (MSM)	Meso-scale EPS (MEPS)
Domain			
Horizontal resolution	2 km	5 km	5 km
Forecast length (initial hours)	18 hours(00, 03, 06, 09, 12, 15, 18, 21 UTC) 10 hours(hourly except for the above)	78 hours(00,12 UTC) 39 hours(03,06,09, 15,18,21 UTC)	39 hours(00,06,12,18 UTC)
Ensemble size	1	1	21
Main Products	Aviation Weather Forecasts and Warnings, Weather Warnings/Advisories, Precipitation Forecasts	Weather Warnings/Advisories, Precipitation Forecasts, Aviation Weather Forecasts and Warnings, Three-hourly Forecasts, Daily Forecasts	Weather Warnings/Advisories, Aviation Weather Forecasts and Warnings, Three-hourly Forecasts, Daily Forecasts
Initial conditions	Local Analysis Hybrid 3D-Var	Meso-scale Analysis Atmosphere: 4D-Var Ocean: HIMSST+ Climatological Profile	Meso-scale Analysis + SV
Sea Surface Temperatures conditions	Fixed (HIMSST)	Fixed (HIMSST) + 1D ocean mixed layer model	Fixed (HIMSST) + 1D ocean mixed layer model

Operational regional NWP models at JMA

Planned in March 2026

	Local Forecast Model (LFM)	Meso-scale Model (MSM)	Meso-scale EPS (MEPS)	**Local EPS (LEPS)** NEW
Domain				
Horizontal resolution	**1 km** NEW	5 km	5 km	**2km**
Forecast length (initial hours)	18 hours(00, 03, 06, 09, 12, 15, 18, 21 UTC) 10 hours(hourly except for the above)	78 hours(00,12 UTC) 39 hours(03,06,09, 15,18,21 UTC)	39 hours(00,06,12,18 UTC)	**21hours (00,06,12,18 UTC)**
Ensemble size	1	1	21	**21**
Main Products	Aviation Weather Forecasts and Warnings, Weather Warnings/Advisories, Precipitation Forecasts	Weather Warnings/Advisories, Precipitation Forecasts, Aviation Weather Forecasts and Warnings, Three-hourly Forecasts, Daily Forecasts	Weather Warnings/Advisories, Aviation Weather Forecasts and Warnings, Three-hourly Forecasts, Daily Forecasts	**MCS prediction**
Initial conditions	Local Analysis Hybrid 3D-Var	Meso-scale Analysis Atmosphere: 4D-Var Ocean: HIMSST+ Climatological Profile	Meso-scale Analysis + SV	**Local Analysis + MEPS Perturbed runs**
Sea Surface Temperatures conditions	Fixed (HIMSST)	Fixed (HIMSST) + 1D ocean mixed layer model	Fixed (HIMSST) + 1D ocean mixed layer model	**Fixed (HIMSST)**

Approaches of km-scale NWP toward better MCS prediction

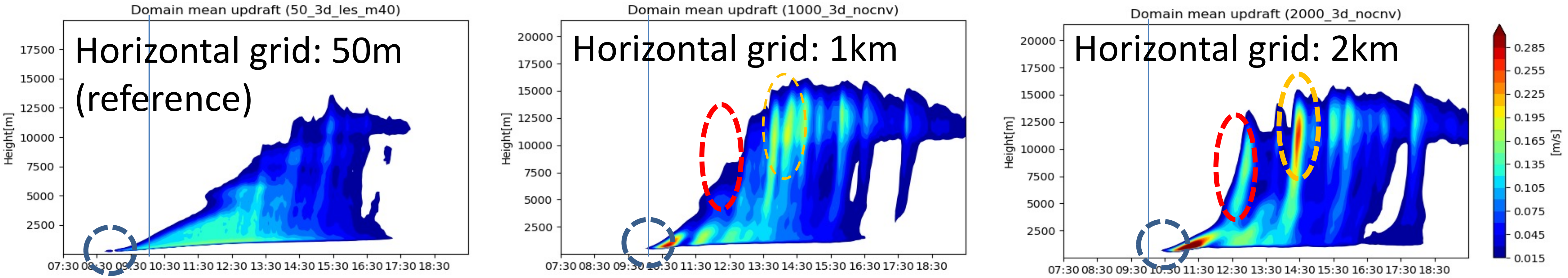
- Considering NWP systems as an integrated system containing model, DA and EPS, approaches with multi aspects have been conducted for better MCS prediction :
  – Km-scale modelling as a convection permitting mode
    - High resolution modelling (~1km), partially resolve convection
    - Physics parameterizations suitable for high resolution models
      – Subgrid vertical transport processes
      – Subgrid orographic parameterizations
  – Assimilation of moisture observations with more sophisticated DA methods
  – Convection permitting EPS for capturing uncertainties in MCS prediction

KM-SCALE MODELLING

- Horizontal resolution enhancement from 2km to 1km
- Improvements to subgrid parametrizations
  - Vertical transport processes
  - Refinement orographic processes

Development of improve horizontal resolution from 2km to 1km

- Ideal experiment and NWP case studies (incl. feasibility studies on Supercomputer Fugaku) showed that the 1kmLFM represented better MCS than the 2km LFM, but issues still exist:
  - Mitigation of slow convective initiation and the rapid transition from shallow to deep convection
  - Mitigation of excessive deep convection



Time-height cross sections of regionally averaged convective updraft from the ideal experiment of cumulus convection proposed by Grabowski et al. (2006).

Introducing the Leonard Term to LFM

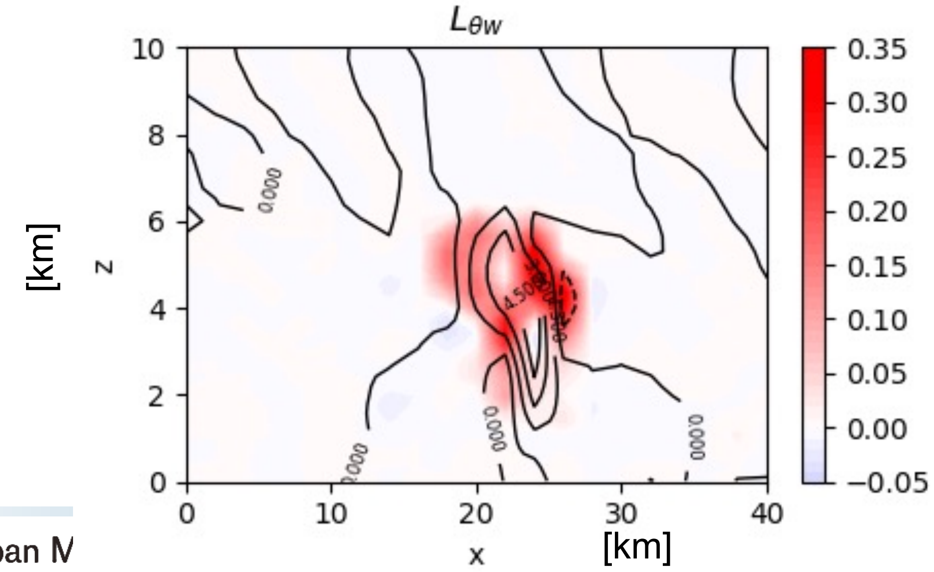
- Introduced into LFM in 2021 (reported at WGNE-36)
- The vertical subfilter flux is parameterized following Moeng et al. (2010) and Verrelle et al. (2017):

$$\tau_{wc} = \underbrace{\frac{K_L}{12}\left(\Delta x^2 \frac{\partial w}{\partial x}\frac{\partial c}{\partial x} + \Delta y^2 \frac{\partial w}{\partial y}\frac{\partial c}{\partial y}\right)}_{\text{the Leonard term}} + \underbrace{\tau_{wc,Kgrad}}_{\text{the Reynolds term}}$$

the Leonard term

It depends on the horizontal gradient (different from a vertical column model).

the Reynolds term as parameterized by a traditional vertical column model

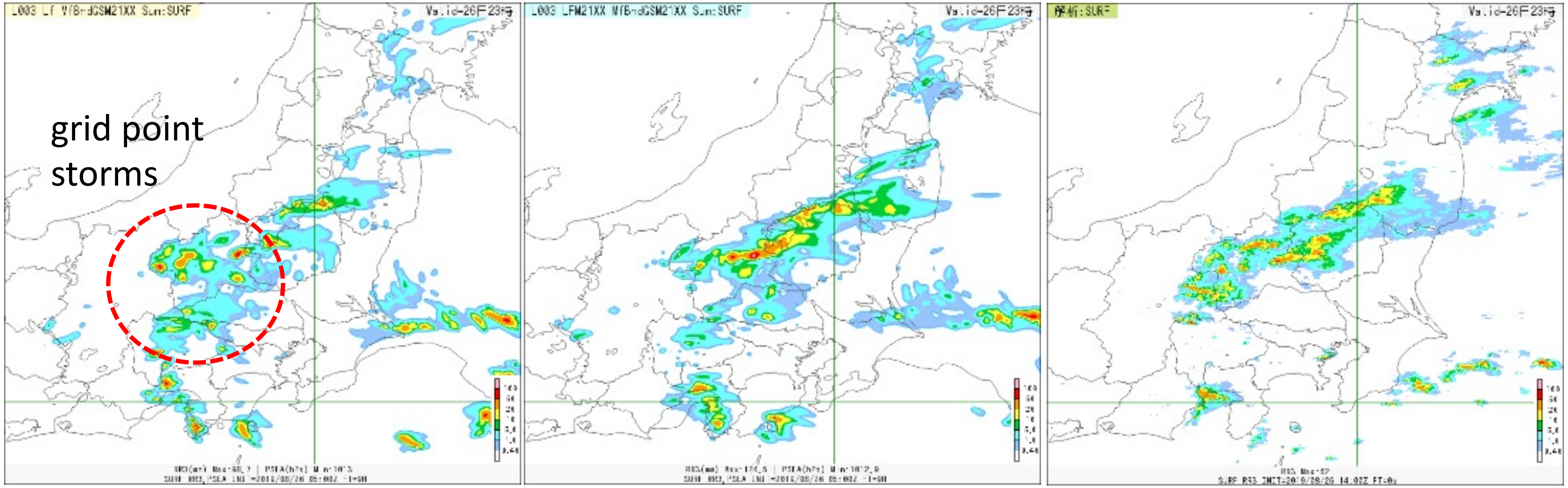


Contour: vertical velocity
Shade: vertical heat flux by the Leonard term

3-hour accumulated precipitation

LFM:

Old(without Leonard term) New(with Leonard term) Radar/Raingauge-Analyzed Precipitation



- The heat and vapor fluxes due to the Leonard term contribute to reduce artificial grid point storms.

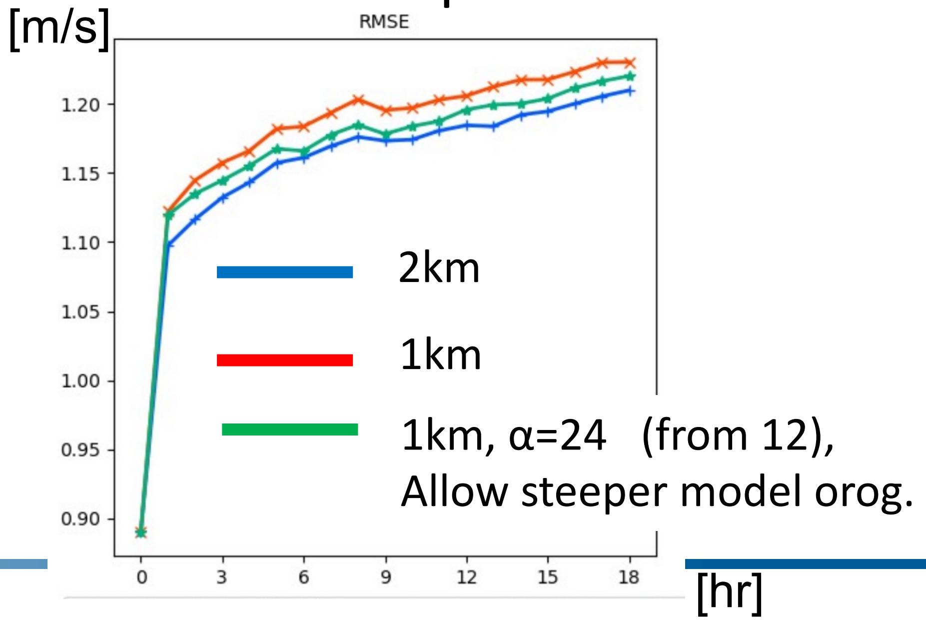
Introduction of TOFD / refinement of orographic processes

- In our recent experiences, subgrid orographic processes can play important roles for MCS prediction through influence on MCS positions.
- Turbulent orographic form drag (TOFD) : Introduced into LFM in 2023 (reported at WGNE-38).
  - necessary even for km-scale models as these processes are not resolved.

$$\frac{\partial \boldsymbol{U}}{\partial t} = \frac{\partial}{\partial z}\frac{\boldsymbol{\tau_o}}{\rho} = -\alpha\beta C_{md}C_{corr}|\boldsymbol{U}(z)|\boldsymbol{U}(z)2.109e^{-\left(\frac{z}{1500}\right)^{1.5}} a_2 z^{-1.2}$$

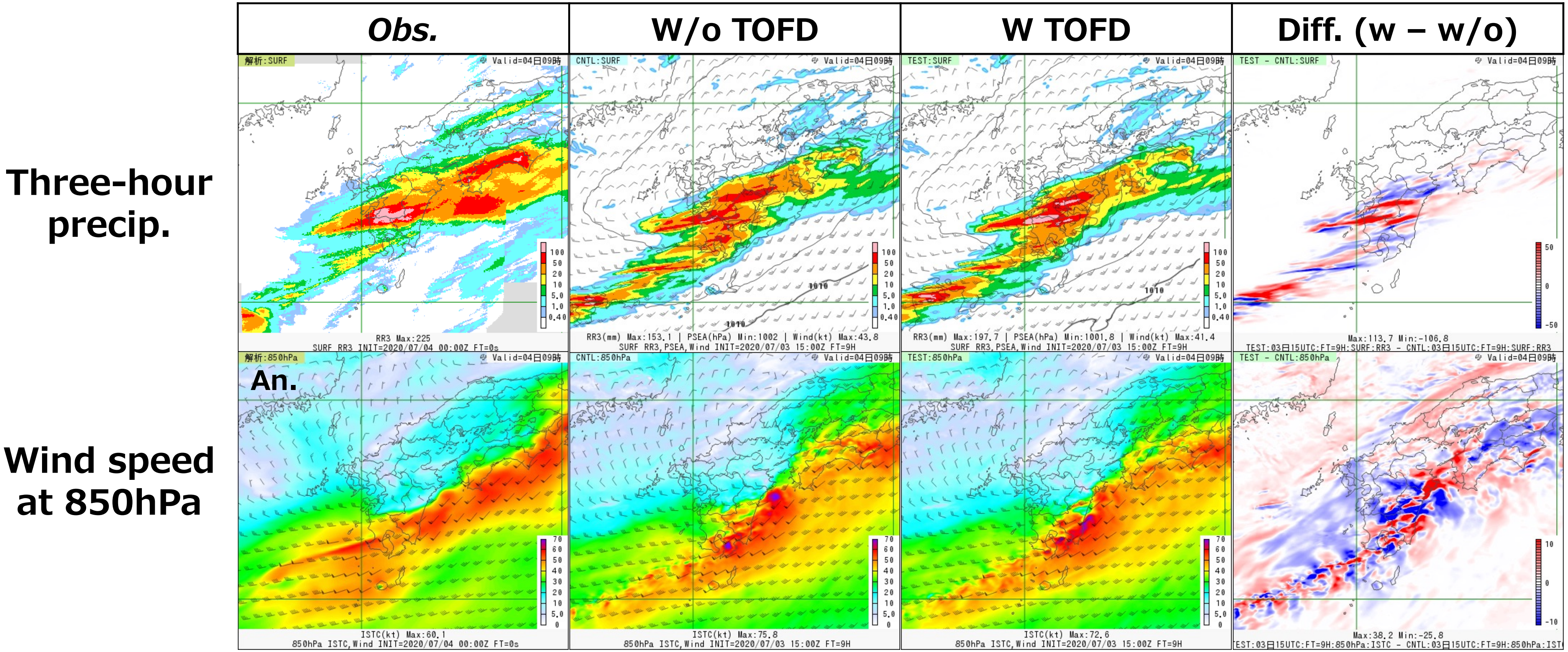
- Orographic processes are to be refined to optimize for better representation of lower tropospheric winds in 1km LFM

RMSE of wind speed at 10m height as functions of forecast lead time



Impacts of TOFD on MCS

Valid 00UTC 4 Jul. 2020 T+9



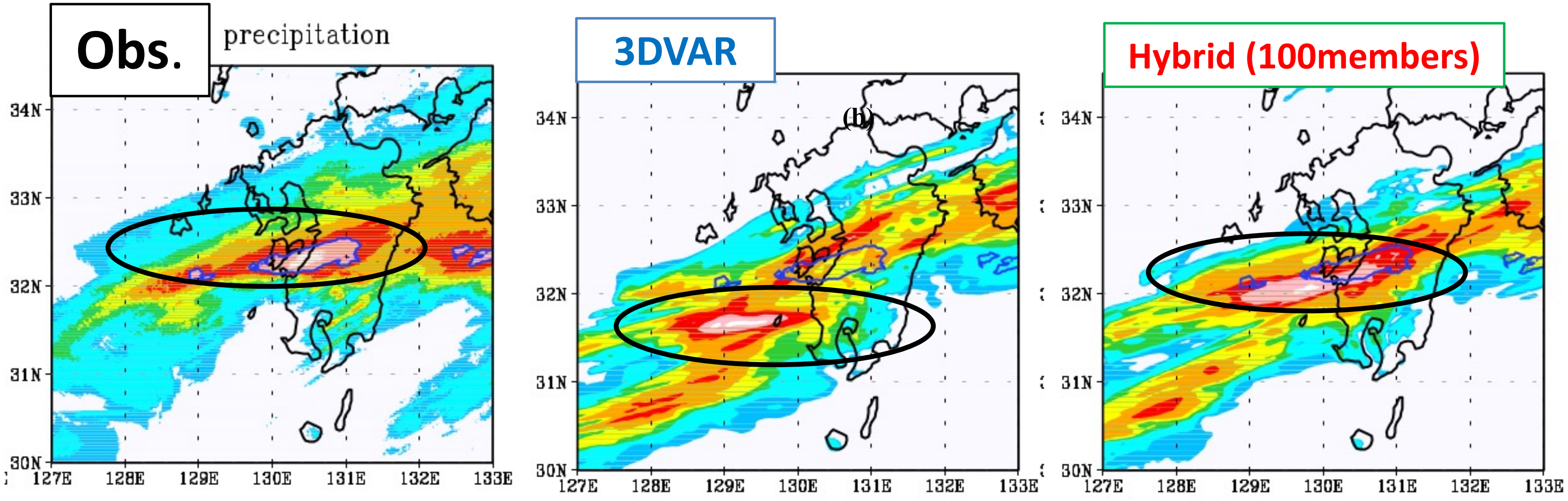
- TOFD influences positions and strength of MCS through representation of low-level winds

ASSIMILATION OF MOISTURE OBSERVATIONS WITH MORE SOPHISTICATED DA METHODS

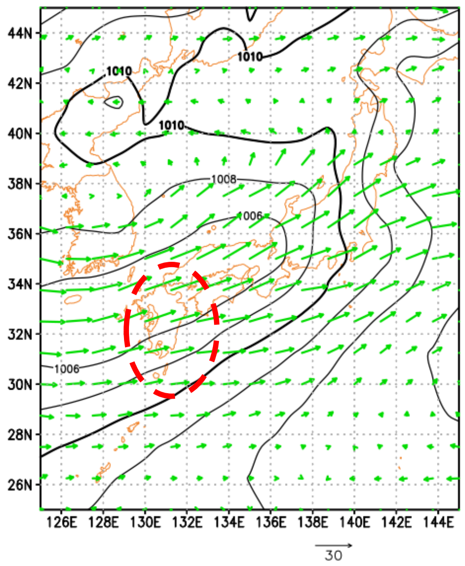
- Hybrid 3DVAR considering flow-dependent errors
- Start assimilation of observations containing moisture information
  - Screen level humidity observations

Case studies of MCS

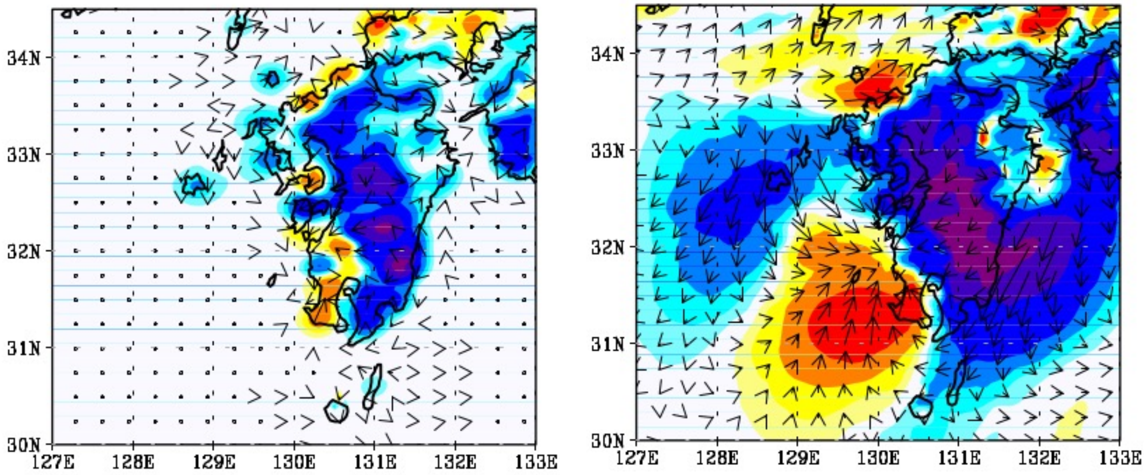
Three-hour precipitation (mm) for 18 - 21 UTC in on 3 July 2020 T+9hr initialized from 12 UTC 3 July 2020



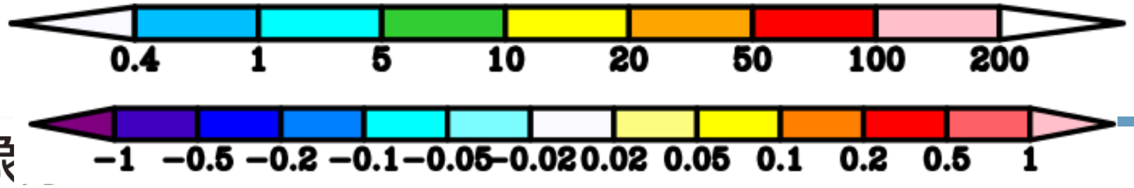
Global analysis at 18 UTC 3 July 2020
Contours: Sea level pressure [hPa]
Vectors: horizontal wind at 500hPa



Analysis increments of surface temperature and winds at T-3 hr



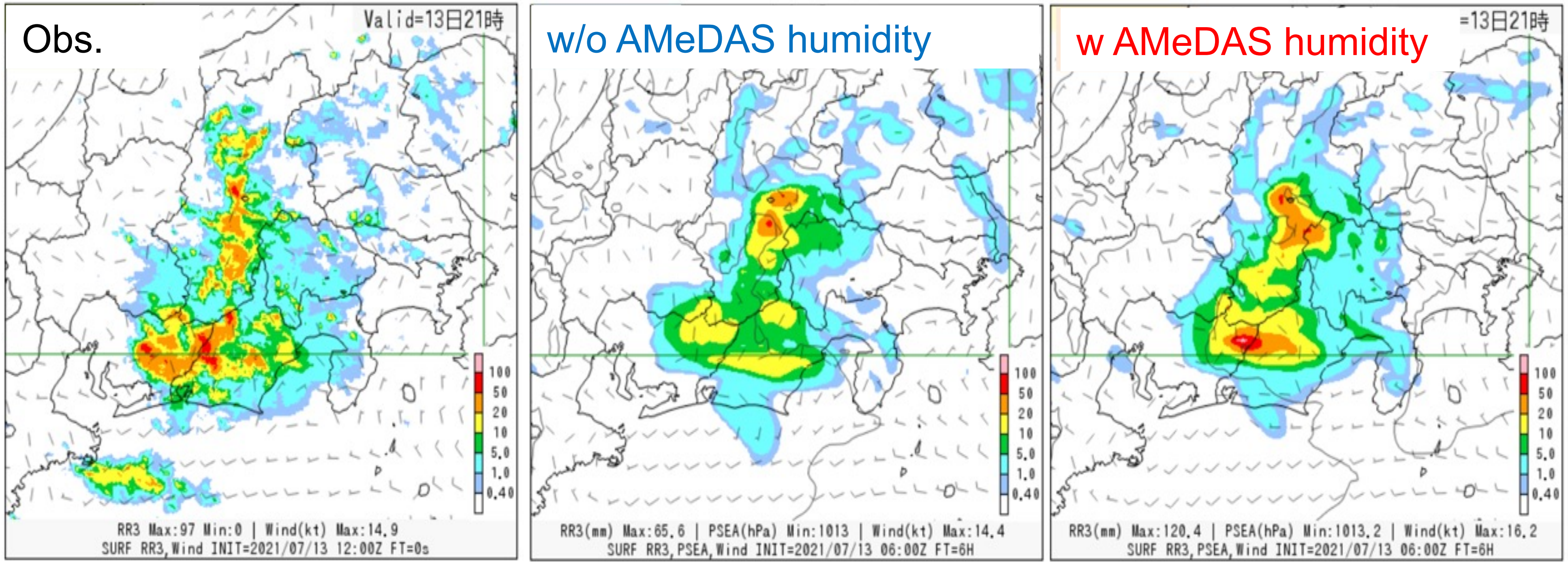
Flow-dependent increments in the hybrid DA improved positions of MCS.



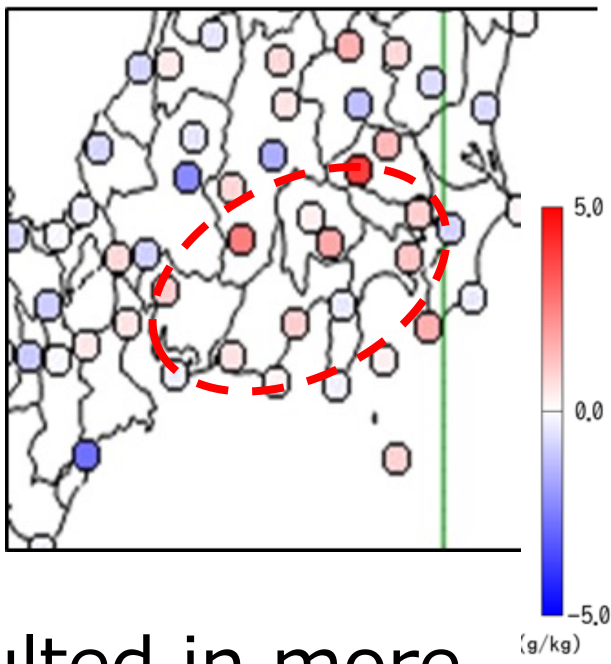
Yokota et al. (2024, JMSJ)

Impact of assimilating screen level humidity on a shower case

Valid: 12UTC (21LST) 13 Jul. 2021



(Obs.) – (Forecast-Guess) departure for screen level humidity [g/kg]



- Assimilation of AMeDAS screen level humidity resulted in more accurate precipitation forecasts
- AMeDAS: The Automated Meteorological Data Acquisition System, a collection of Automatic Weather Stations (AWSs) operated over Japan by JMA.

CONVECTION PERMITTING EPS FOR CAPTURING UNCERTAINTIES IN MCS PREDICTION

- Specifications
- Parents & Child model relation between MEPS and LEPS

LEPS (Local EPS) as convection permitting mode

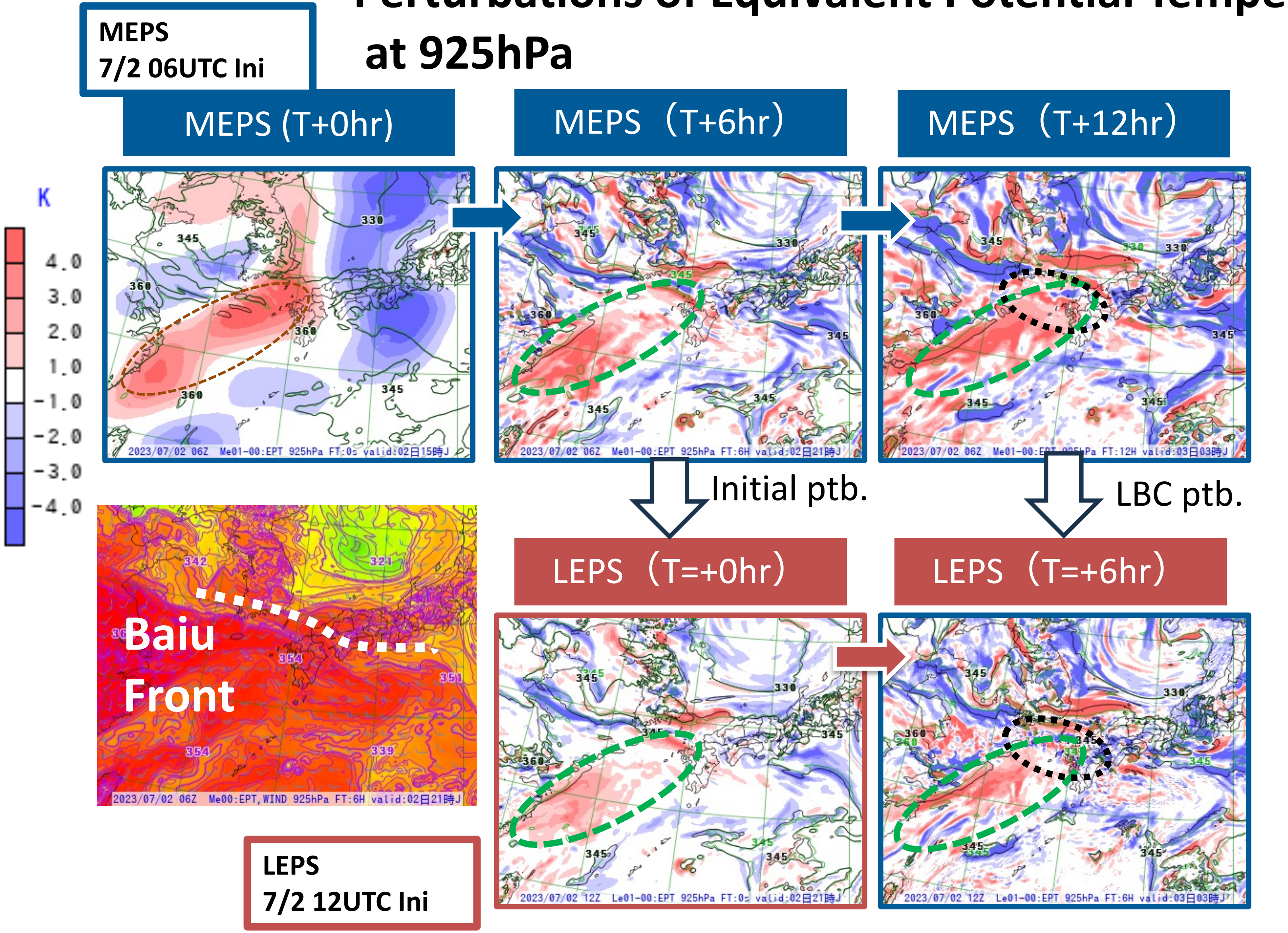
Aim: Capturing uncertainties in MCS predication arise from environmental conditions (Meso-beta (~100km) scale)

- Initial and lateral boundary perturbations are provided from MEPS (parent model for LEPS) with amplification adjustment

	MEPS (Meso-scale EPS, in operation)	LEPS (Local EPS, in experimental operation)
Horizontal resolution	5km	2km
Convective parameterization	Yes (non-convection permitting mode)	Yes (convection permitting mode: strength of mass fluxes are much weaker than MEPS by controlling closure)
Ensemble members	21	21
Initial conditions	Meso-scale analysis	Local analysis
Initial perturbations	Singular Vectors from the global and regional models	From MEPS perturbed runs (regridded to 2km)
Model Perturbations	SPPT	None
Lateral boundary perturbations	Singular Vectors from the global model	From MEPS perturbed runs
Lower boundary perturbations	None	None

Parents & Child model relationship between MEPS and LEPS

Perturbations of Equivalent Potential Temperature [K] at 925hPa



- Large-scale error growth are similar between MEPS (parent) and LEPS (child)
- Small-scale error growth response to the ptb. in MEPS (parent) are found in LEPS (child)

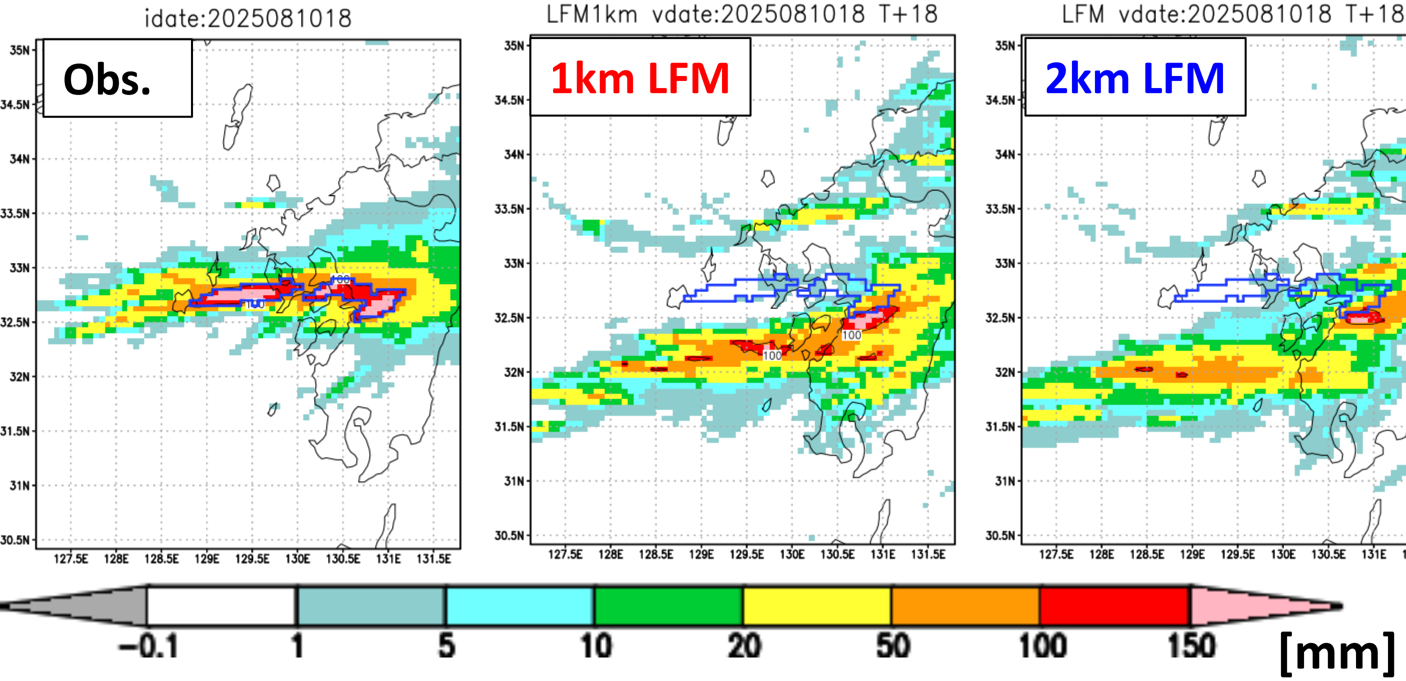
MCS prediction so far

- 1km LFM and 2km Local EPS as convection permitting mode are under experimental operation in 2025
- Preparing for operation in March 2026

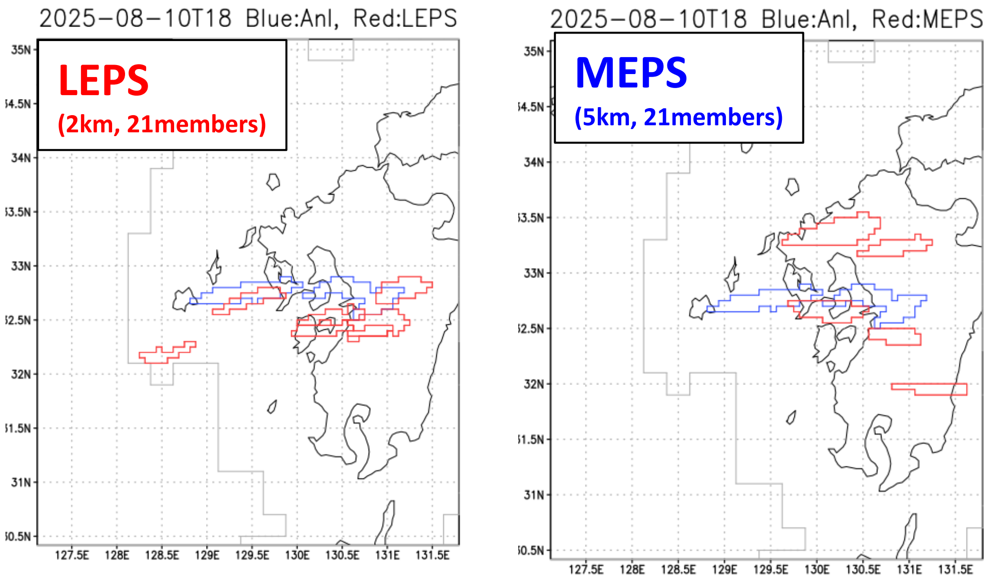
(*) Area where 100mm/3h > 500km^2
& maximum precip. > 150mm/3h
& aspect ratio of object > 2.5

Recent case of heavy rain 2025:
Validtime: 18UTC 10 Aug. 2025, Leadtime: T+18hr

3-hour accumulated precipitation [mm]



Line-shaped MCS objects (*)
Blue: Obs., Red: Fcst.

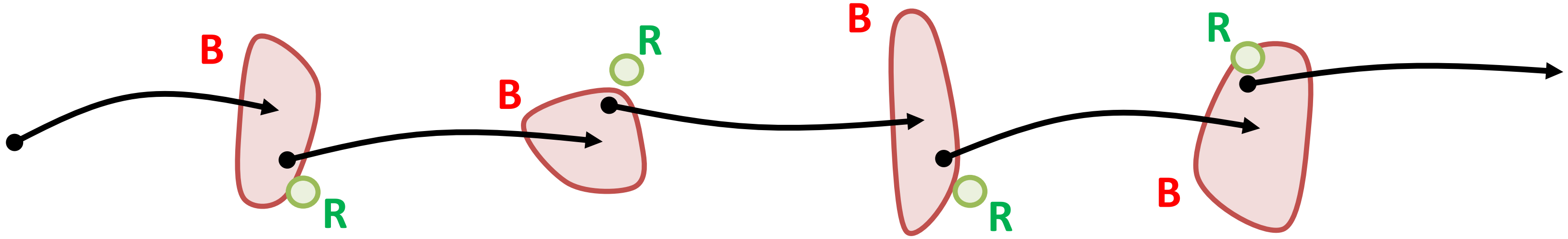


Future directions

- Incorporation of 1km LFM and 2km Local EPS as convection permitting mode into the operational NWP system is a milestone for better MCS prediction
- For future steps, how physics and ML/AI approaches co-work efficiently for MCS prediction should be considered
  - Physics-based approaches
    - Further improvement of physics parameterization more suitable for km-scale NWP models
    - More advanced use of observation for extracting moisture information
      - Use of hyperspectral IR sounders on Himawari-10, to be launched ~2030
      - Approaches toward all-sky & all-surface data assimilation
    - Possibility of providing training data to ML/AI models
  - ML/AI approaches
    - Predictability of AI/ML models for MCS prediction ? If yes, what kind of training data / methods are required ? etc…

WGNE-37

Hybrid 3DVAR approach for flow-dependent B-matrix



Cost function:

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}^b)^T \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}^b) + \frac{1}{2}[\mathbf{H}(\mathbf{x}-\mathbf{x}^b)-\mathbf{d}]^T \mathbf{R}^{-1}[\mathbf{H}(\mathbf{x}-\mathbf{x}^b)-\mathbf{d}]$$

Background error covariance:

$$\mathbf{B} = \beta_c^2 \mathbf{B}_c + \beta_e^2 \mathbf{B}_e$$

Climatology-based B Ensemble-based B

$$\beta_c^2 = \beta_e^2 = 0.5$$

Observation error covariance

$$\mathbf{d} \equiv \mathbf{y}^o - H(\mathbf{x}^b)$$

FG departure

The Ensemble-based B is obtained from the **100 members of the operational Mesoscale EPS using lagged forecasts** (20 members / initial date.)


WGNE-38

Recent upgrades of JMA's NWP system

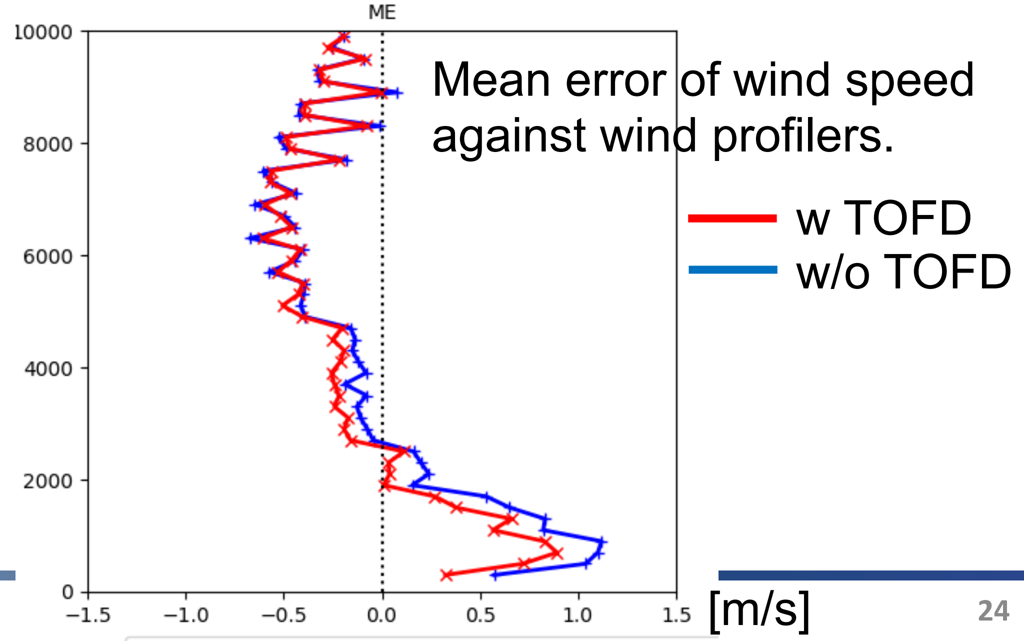
- Upgrade of GSM (Mar. 2023)
  - Increase of horizontal resolution to TL959(20km) ➔ TQ959(13km)
  - Physics upgrade, incl. parametrized surface drag
  - Upgrade of orography ancillaries
- Upgrades of the regional NWPs which contribute to improving representation of MCS (Mesoscale Convective Systems) (Mar.2023)
  - Introduction of TOFD scheme into LFM
    - TOFD: Turbulent Orographic Form Drag
  - Assimilation of screen level humidity in Mesoscale and Local Analysis

Introduction of TOFD

- Effects of subgrid orography had not been considered in LFM (dx: 2km)
  - Gravity wave drag and blocked flow drag are partially resolved in LFM, however, turbulent orographic form drag (TOFD) is not.
  - One of possible reasons for low-level strong wind bias in LFM
- TOFD based on Beljaars et al. (2004) was introduced into LFM
  - parameters related to subgrid orography are computed from MERIT DEM.

$$\frac{\partial \boldsymbol{U}}{\partial t} = \frac{\partial}{\partial z}\frac{\boldsymbol{\tau_o}}{\rho}$$

$$= -\alpha\beta C_{md}C_{corr}|\boldsymbol{U}(z)|\boldsymbol{U}(z)2.109e^{-\left(\frac{z}{1500}\right)^{1.5}}a_2 z^{-1.2}$$



Impacts of TOFD on MCS

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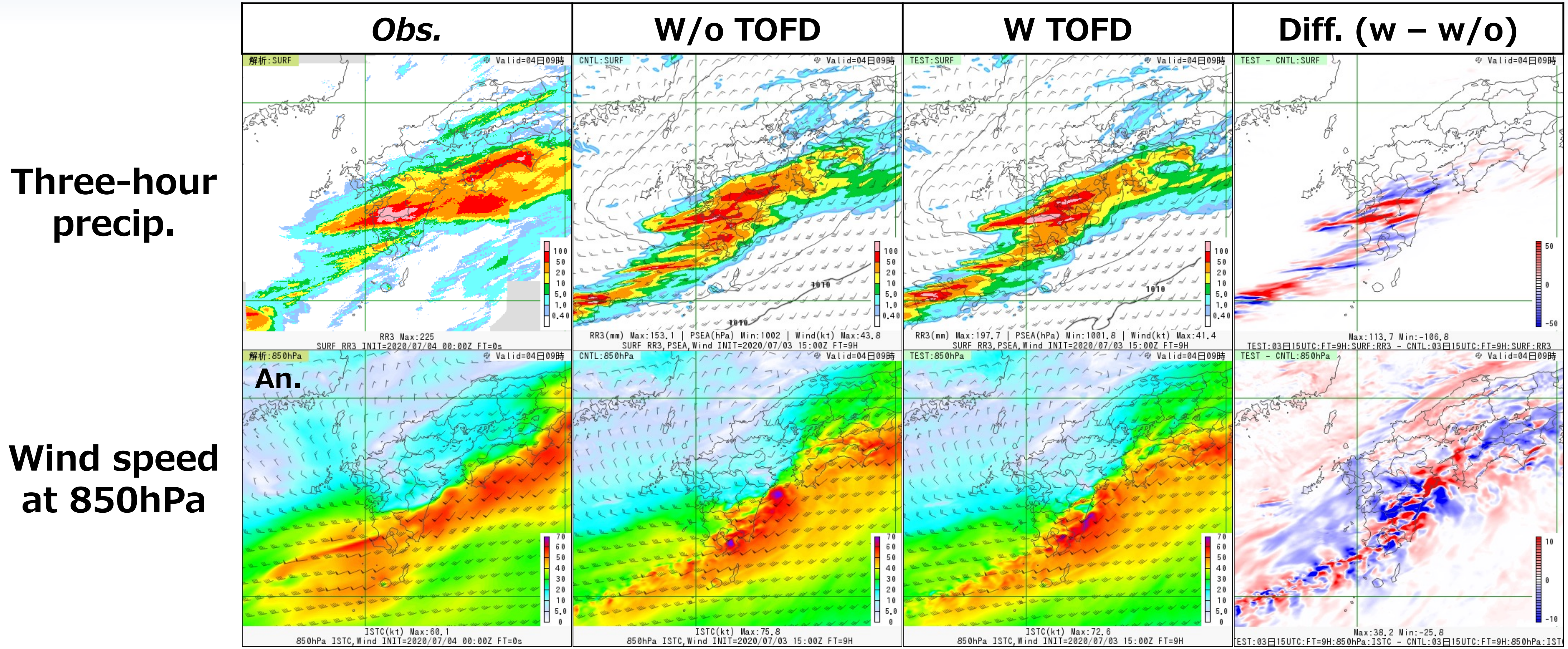

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YAMASAKI Yukihiro and KUSABIRAKI Hiroshi

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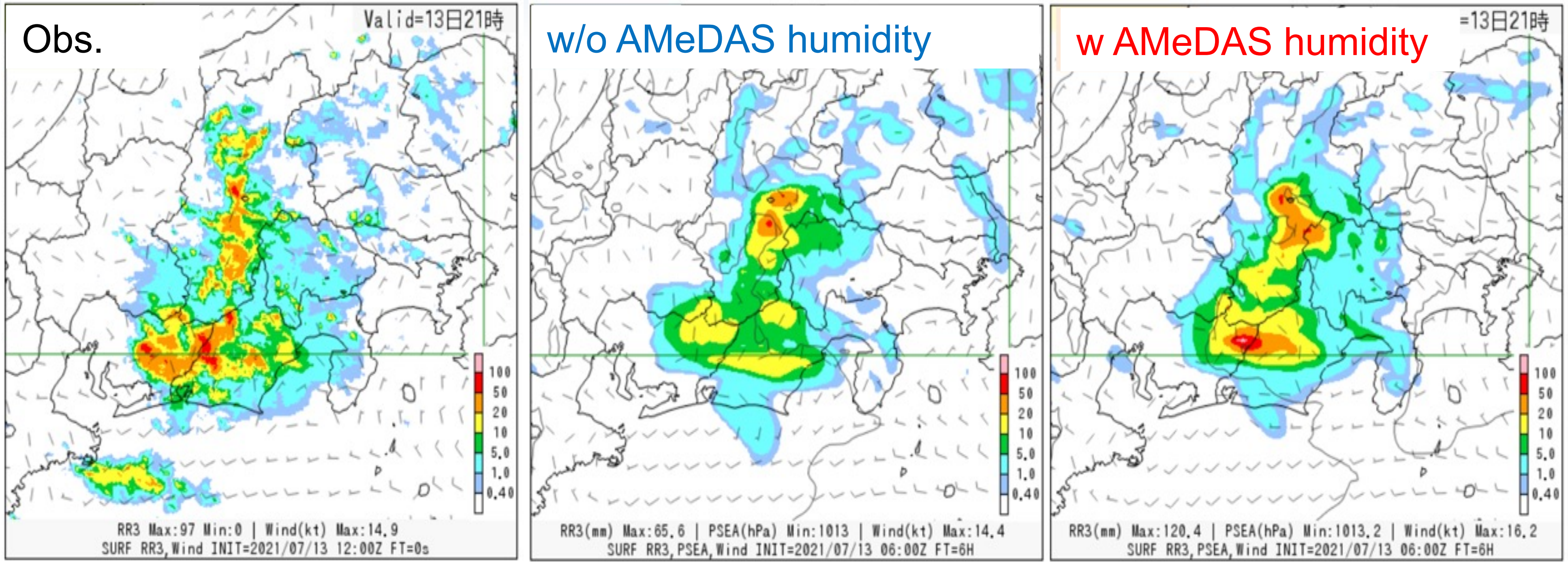
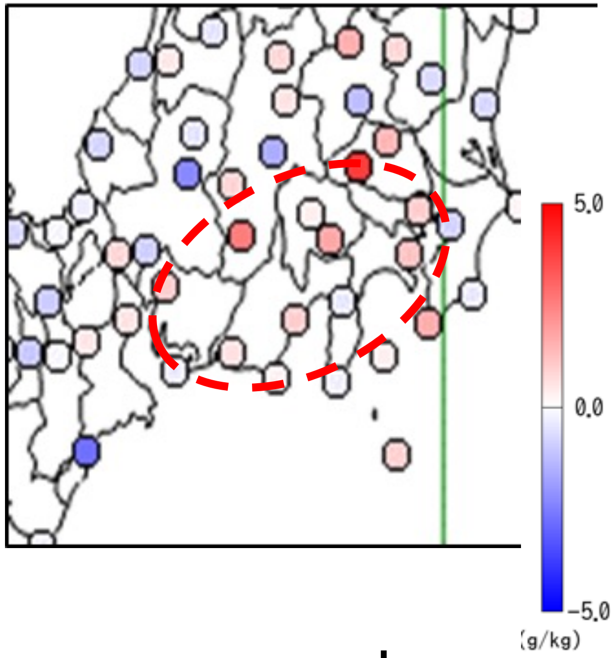


O-B (Forecast-Guess departure) for screen level humidity [g/kg]



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TOGUCHI Ryo and IRIGUCHI Takeshi

WGNE-39

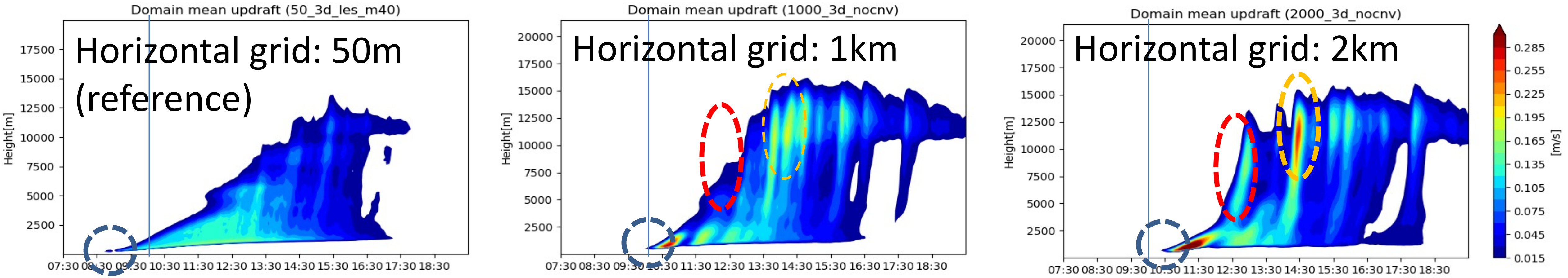
NAPS11s

- Operational March 2023
  - Contract w/ Fujitsu
- Two PRIMEHPC FX1000's
  - A64fx processor
- Spec per each subsystem
  - Peak 14.27 petaflop/s
  - Power 904.72 kW
- HBM2 memory
  - 1024 GB/s/node
  - 2x effective performance of NAPS10

Located in Fujitsu facility, unlike previous NAPS supercomputers

Development of improve horizontal resolution from 2km to 1km

- On NAPS11s, resolution improvement of LFM (the JMA's finest mesh regional model) is planned in Mar. 2026.
- Ideal experiment and NWP case studies (incl. feasibility studies on Supercomputer Fugaku) showed that the 1kmLFM represented better MCS than the 2km LFM, but issues still exists:
  - Mitigation of slow convective initiation and the rapid transition from shallow to deep convection
  - Mitigation of excessive deep convection
- Toward further improvement, vertical transport processes associated with convection will be a key.



Time-height cross sections of regionally averaged convective updraft from the ideal experiment of cumulus convection proposed by Grabowski et al. (2006).

Recent updates of JMA’s NWP system development

- New HPCs launch (Mar. 2023 and Mar. 2024)
  - NAPS (Numerical Analysis and Prediction System) 10 -> NAPS11s, NAPS11
    - NAPS11s : Specialized for predicting MCS (Mesoscale Convective Systems)
    - NAPS11 : Implements all other functions
- Upgrades of the regional NWPs (Mar.2024)
  - Introduction of SSP-RK scheme in HE-VI time integration (Kimura et al. 2024, WGNE Blue Book).
  - Assimilation of ground-based microwave radiometer data (Nakamura et al. 2024, WGNE Blue Book)
- Research on machine learning based models

Introduction of SSP-RK scheme in HE-VI time integration

- ASUCA, a regional non-hydrostatic model used in the JMA's regional NWPs (Ishida et al. 2022), employed a HE-VI (Horizontally Explicit Vertically Implicit) method for solving fast modes such as acoustic waves.
  - Combined with the Wicker and Skamarock (2002)'s third-order Runge-Kutta scheme (RK3)
- For solving the fast modes (less meteorologically important waves) with higher computational stability and efficiency, a Strong Stability Preserving Runge-Kutta scheme (Shu and Osher 1998; SSP-RK) was implemented in the HE-VI method.

Wicker and Skamarock(2002)	SSP-RK(3,2)
$f^{(1)} = f^n + \frac{\Delta t}{3}\phi\left(f^n\right)$	$f^{(1)} = f^n + \frac{\Delta t}{2}\phi\left(f^n\right)$
$f^{(2)} = f^n + \frac{\Delta t}{2}\phi\left(f^{(1)}\right)$	$f^{(2)} = f^n + \frac{\Delta t}{2}\phi\left(f^{(1)}\right)$
$f^{n+1} = f^n + \Delta t\phi\left(f^{(2)}\right)$	$f^{n+1} = \frac{1}{3}f^n + \frac{2}{3}f^{(2)} + \frac{\Delta t}{3}\phi\left(f^{(2)}\right)$

Introduction of SSP-RK scheme in HE-VI time integration

- Our linear stability analysis using a one-dimensional shallow water system has clarified that SSP-RK combined with HE-VI provides higher computational stability than RK3.
- Not only the simplified linear system, but also in the non-linear three-dimensional systems using ASUCA, we empirically confirmed that SSP-RK is stable with larger Courant numbers than RK3.
- These results suggest that SSP-RK enables employment of larger time-step for HE-VI.

$$\frac{\partial u}{\partial t} = -g\frac{\partial h}{\partial x},$$
$$\frac{\partial h}{\partial t} = -H\frac{\partial u}{\partial x}.$$

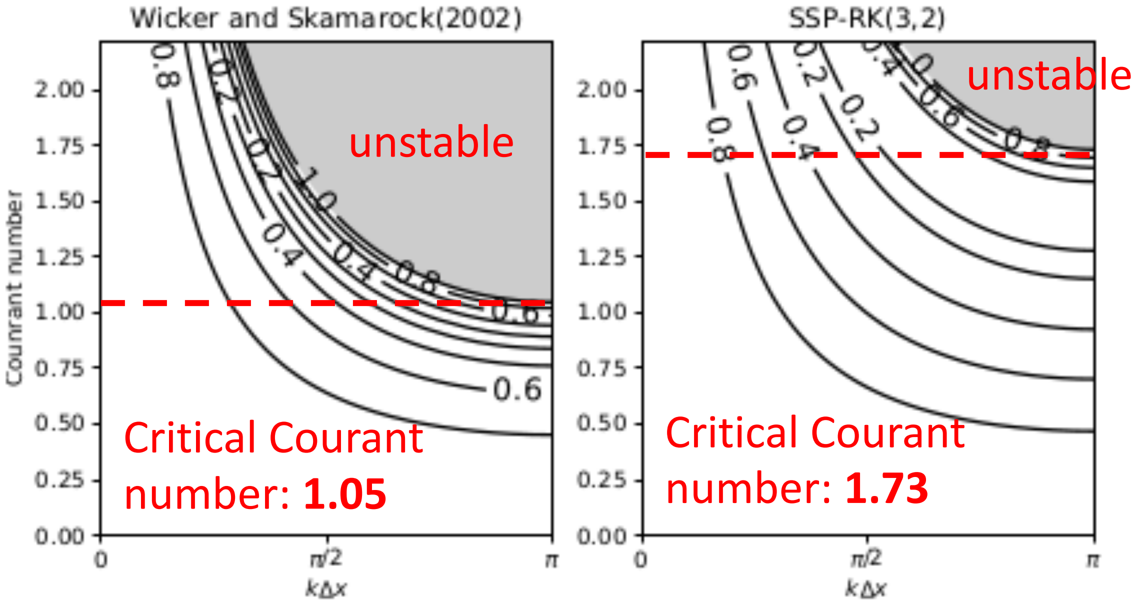
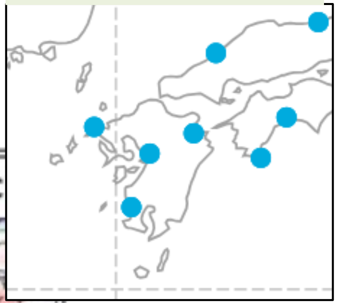


Figure 2: Amplification factors of WS02 (left) and SSP-RK(3,2) (right). The horizontal and vertical axes are $k\Delta x$ and Cr, respectively. Regions with amplification factors larger than unity (i.e., where numerical solutions are unstable) are shaded.

Assimilation of ground-based microwave radiometer data

- MCS: Important targets for JMA's NWP systems (as stated in the JMA NWP strategic plan)
- JMA started to assimilate precipitable water vapor (PWV) retrieved from the ground-based microwave radiometers (MWRs) adopted in western Japan for water vapor monitoring.
- In a case below, ongoing assimilation of MWR modified PWV distribution around MCSs and improved precipitation forecasts.

MWR sites



Three hour accumulated precipitation [mm] valid for 00UTC 10 Jul. 2023
Forecast lead time : 6hr