Assimilation of dual multi-parameter phased array weather radar (MP-PAWR) observations for high precision convective forecasting

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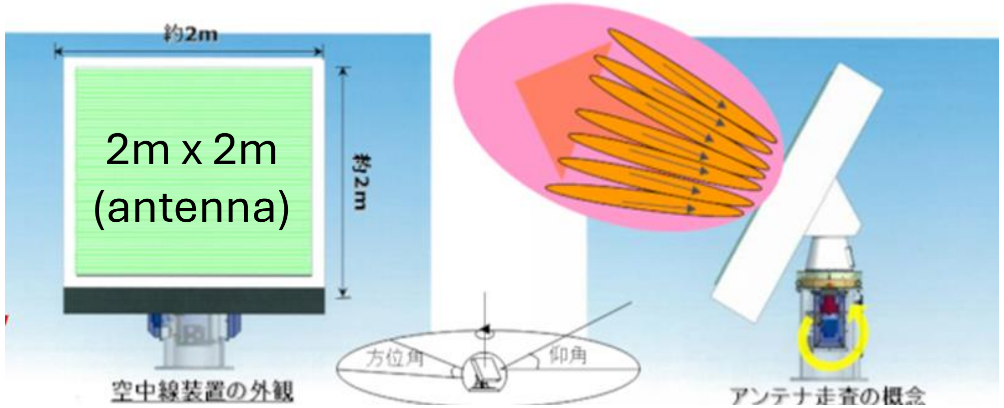
Predictability and Controllability PC 1-2
ISDA Kobe 2024

Phased Array Weather Radar (PAWR)

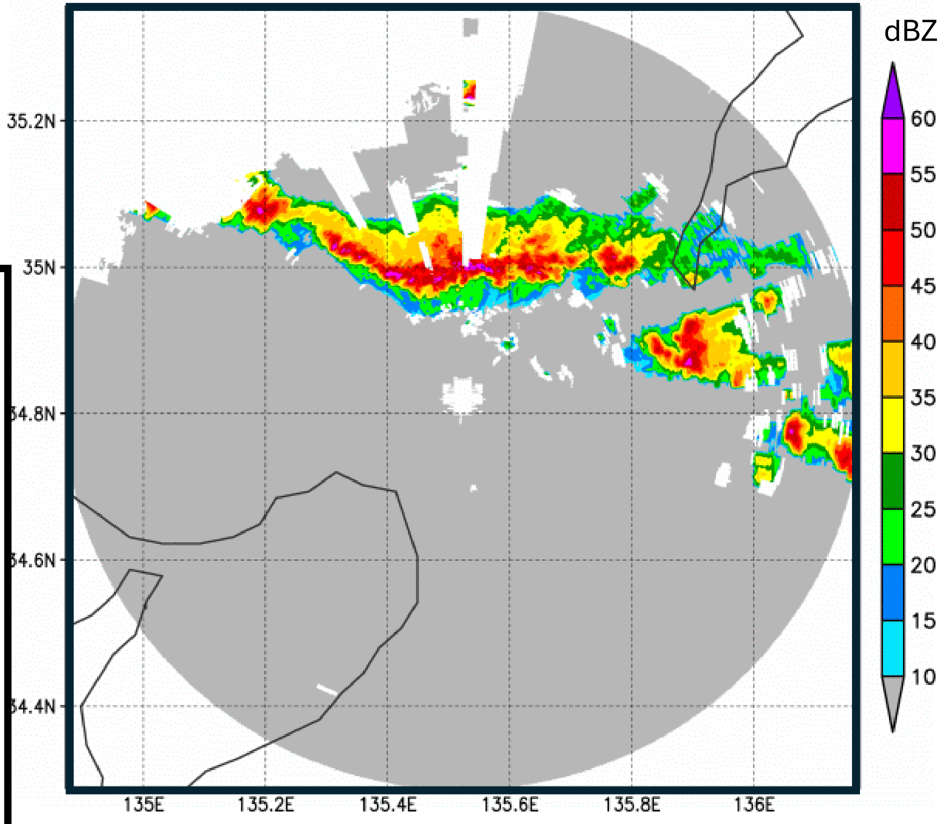
Fan Beam Technology (dense observations)



Radar beam direction adjusted electronically rather than physically

Images from NICT

- X-Band Frequency Radar developed in Japan
- Reflectivity (dBZ) and Doppler radial wind velocity (Vr)
- 100m range resolution
- ~100 elevation angles
- Full-sky scan every 30 seconds



Left: Radar reflectivity observations every 30-seconds from Suita MP-PAWR for convective storm over Hyogo, Osaka, Kyoto

Phased Array Weather Radar (PAWR)

Dual PAWR Coverage in Kobe/Osaka

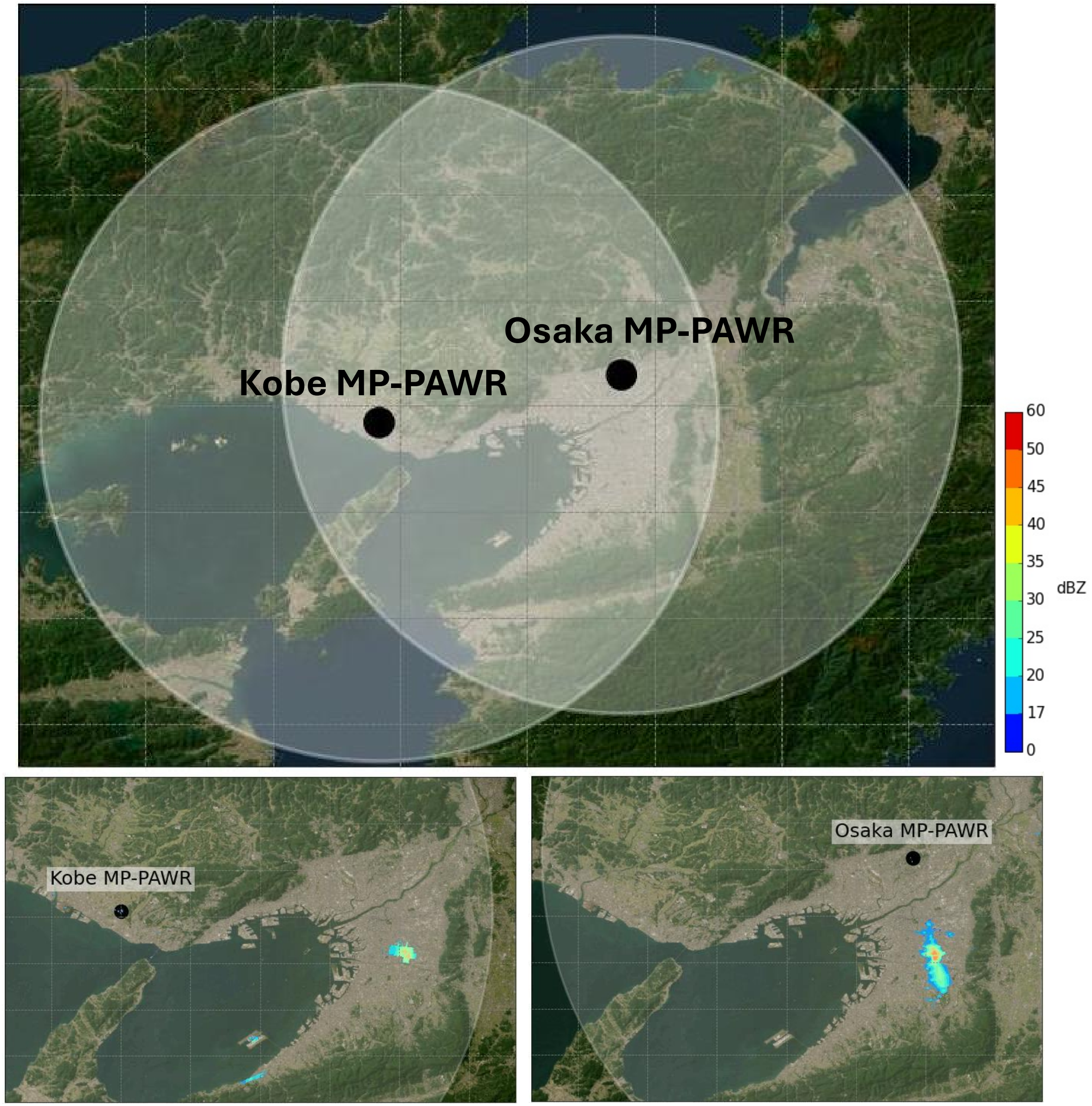
- 5 PAWR across Japan
- Osaka and Kobe PAWR were developed in 2012 and 2014, creating a common observation region where there is overlapping radar coverage providing:

  x2 radar reflectivity (Ze)
  x2 Doppler radial velocity (Vr)

- Both radars recently upgraded to Multi-Parameter PAWR (dual polarization) with radius of 80km

Advantages of dual radars:

- Extended combined coverage to observe rainfall activity over Kansai
- Correct for rain attenuation (loss of signal)
- Wind observations from two radars will enable improved construction of 3D wind field in simulations



Right: Radar reflectivity (dBZ) observations from Suita and Kobe PAWR for a convective storm on 20 August 2016

Project: Osaka Expo 2025

Objectives :

1) Provide real-time rain forecasts for Osaka Expo 2025, upcoming 6-month World Expo taking place next year
2) Assimilate observations from the Kobe and Suita MP-PAWR radars within the SCALE-LETKF real-time NWP system for a period of 1-month to provide staff and visitors with real-time 30-min rain forecasts for the Kansai region

Osaka Expo 2025 (Apr –Oct 2025)
(Yumeshima Island, Osaka, Japan)

We are here
(Port Island)

Japan Association for the 2025 World Exposition
Source: https://www.expo2025.or.jp/en/overview/masterplan/

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SCALE-LETKF Real-Time NWP System

SCALE-LETKF combines the SCALE-Regional Atmospheric Model (built at RIKEN) with the LETKF

Domain 3 (Outer)

The outer domain is a pure ensemble downscaling from the JMA MSM model (5-km resolution) data

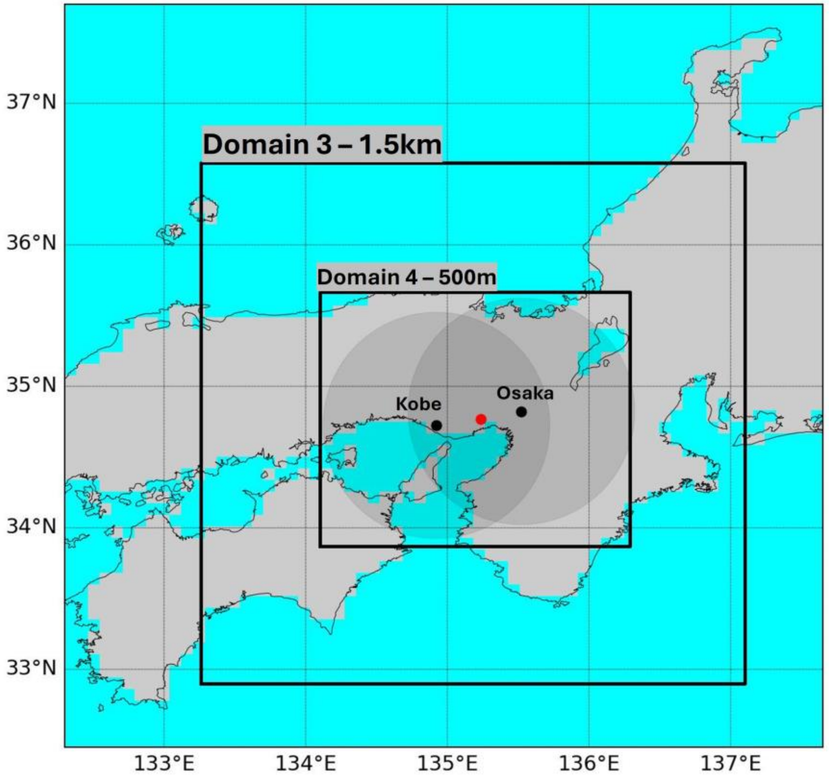
Grid spacing: 1.5 km
Levels: 45 levels up to ~16.8km
Ensemble size: 1000 (perturbed using past JMA data)
Forecast length: 9hrs

Domain 4 (Inner)

The inner domain performs 30-second data assimilation and 30-min extended ensemble forecasts. Initial and boundary conditions are downscaled from the outer domain forecast.

Grid Spacing: 500 m
Levels: 45 levels up to ~16.8km

Data Assimilation Cycling	Extended Forecast
Ensemble size: 1000 **Update frequency: 30sec** **Observations assimilated**: Reflectivity and Doppler wind velocity from Kobe and Suita MP-PAWR. • Vrx2 assimilated at each grid • Zex1 assimilated at each grid (based on proximity to radar)	**Ensemble size**: 10 **Update frequency**: 30sec **Forecast length: 30min** **Forecast output interval**: 30sec



Data

Radar data is quality controlled (QC), thinned and superobbed to model resolution (500-m)

Horizontal and vertical location: 2-km
Max observations per grid: 100

SCALE-LETKF Real-Time NWP System

External Data

Observations (MP-PAWR)

National Institute of Information and Communications Technology

JIT-DT (Just-In-Time-DT)

Every 30-seconds

Atmospheric Data

JMA Mesoscale Model Analysis/Forecasts (atmosphere)

Land Data

NCEP GFS (land)

Fast data transfer

Every 3-hours

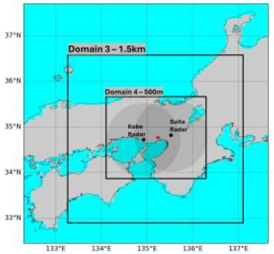
Every 6-hours

Computational Processing

Fugaku Supercomputer

SCALE-LETKF

Outer Domain
1000-member 9hr forecasts run every 3hrs
Downscaling for D4 Init/Bdy
Inner Domain
1000-member DA cycling
10 member extended forecasts



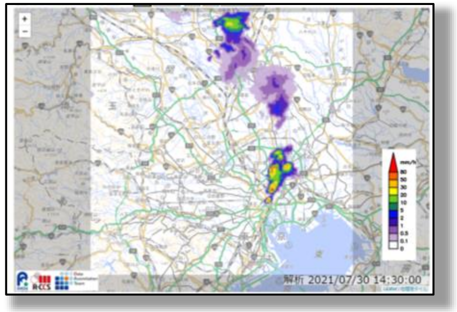
30-min Forecast (updated every 30seconds)

Every 30-seconds

Forecast on Smartphone App (30-second update)

Output

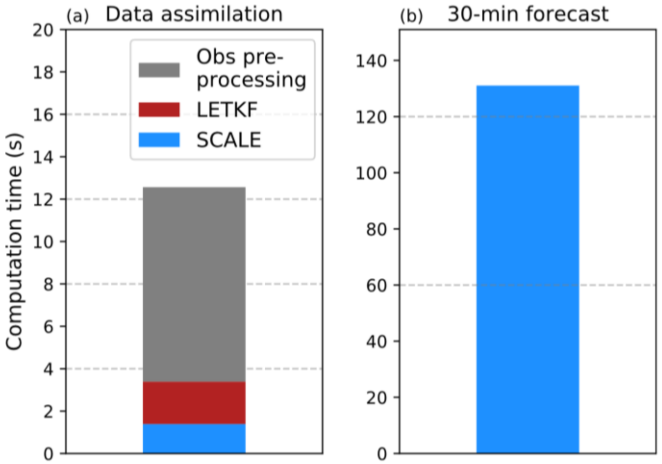
weather.riken.jp



MTI Ltd app

Ultra rapid computation and dissemination of forecasts possible due to:

- Just-In-Time Data Transfer (JIT-DT) – new software to transfer MP-PAWR observation files to Fugaku every 30-seconds
- Single precision for LETKF, SCALE-RM, eigensolver
- Avoid computational expensive file I/O data transfer by merging the DA and forecasts into single binary executable (MPI initiation not required)
- KevD (newly developed eigenvalue solver)
- Exclusive use of up to 20,000 nodes on Fugaku

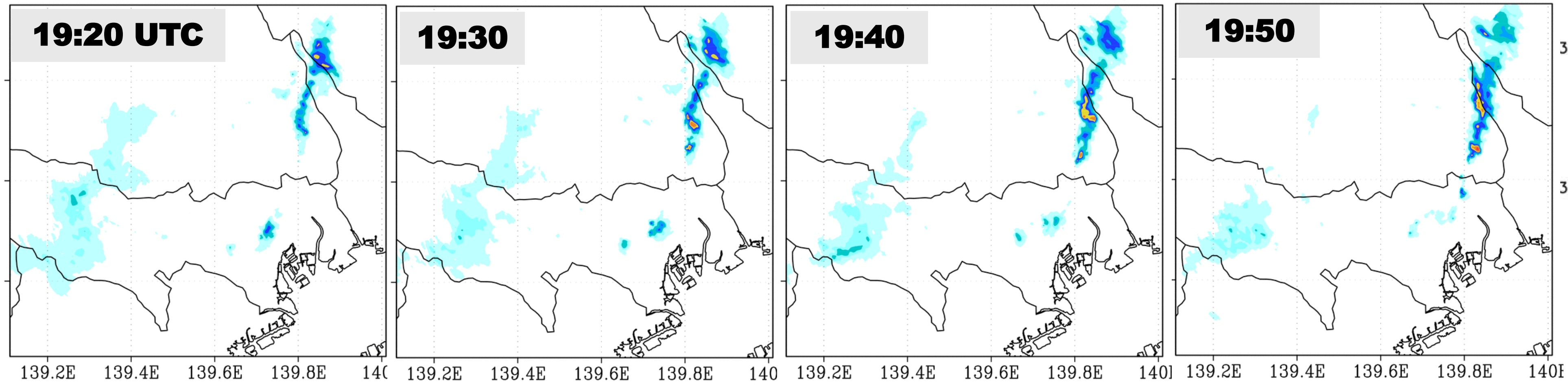


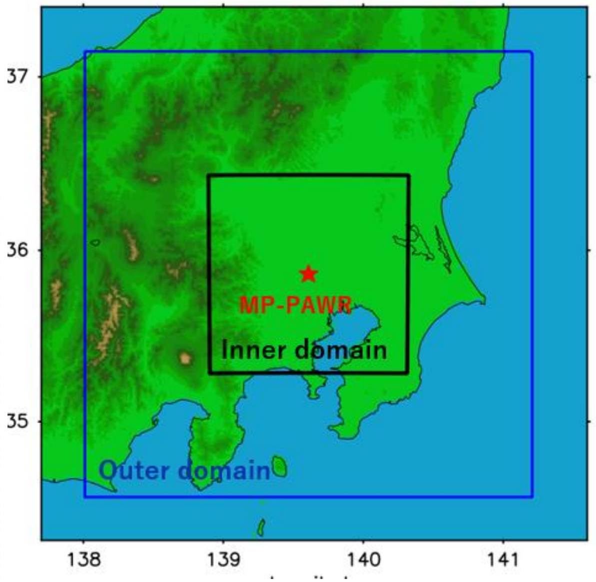
Honda, T., Amemiya, A., Otsuka, S., Lien, G.-Y., Taylor, J., Maejima, Y., et al. (2022). Journal of Advances in Modeling Earth Systems, 14, e2021MS002823. https://doi.org/10.1029/2021MS002823

Project Tokyo 2021: Single MP-PAWR assimilation

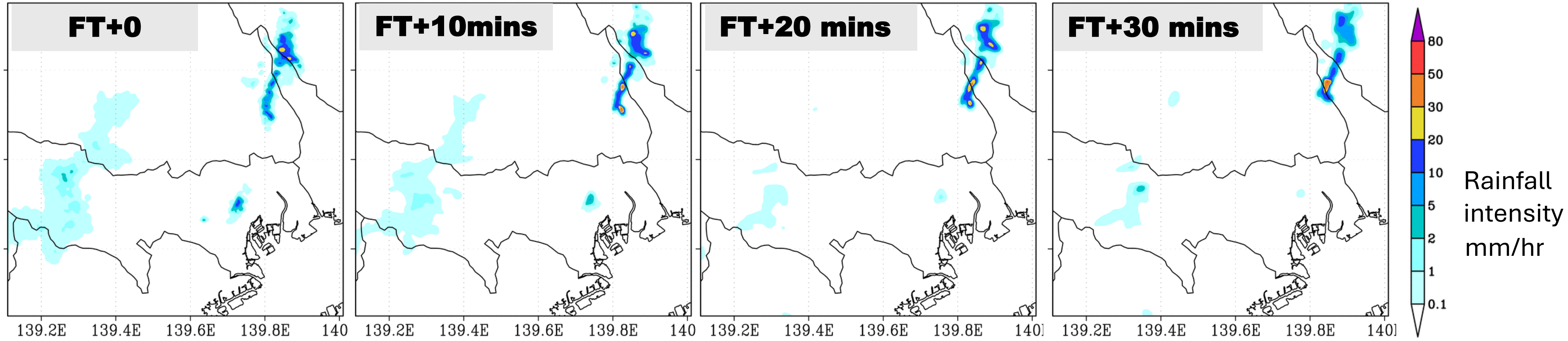
Performed previous demonstration for Tokyo region in 2021 during Olympic Games
Saitama MP-PAWR observations assimilated every 30-seconds within a 500-m mesh

RADAR OBSERVATIONS (SAITAMA MP-PAWR)





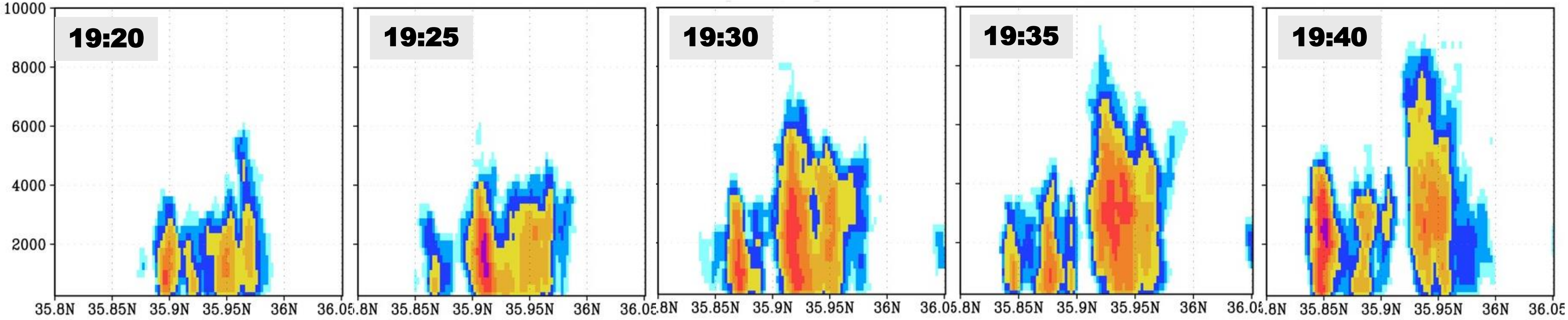
SCALE-LETKF Real-Time System ENSEMBLE MEAN EXTENDED FORECAST



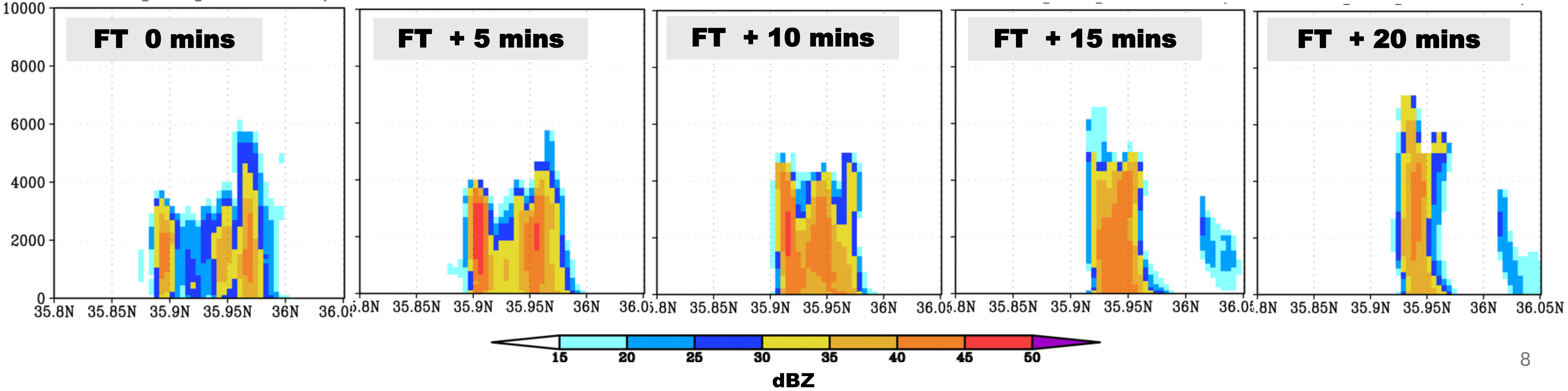
Predicting rapid convective growth and intensity changes

Vertical cross section of reflectivity (dBZ)

RADAR OBSERVATIONS

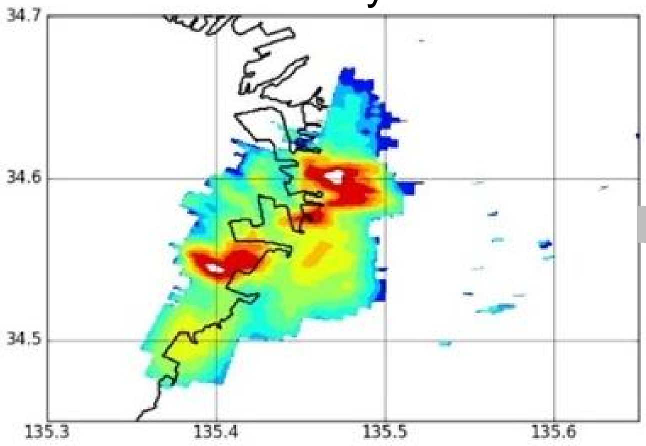


SCALE-LETKF Real-Time System FORECAST

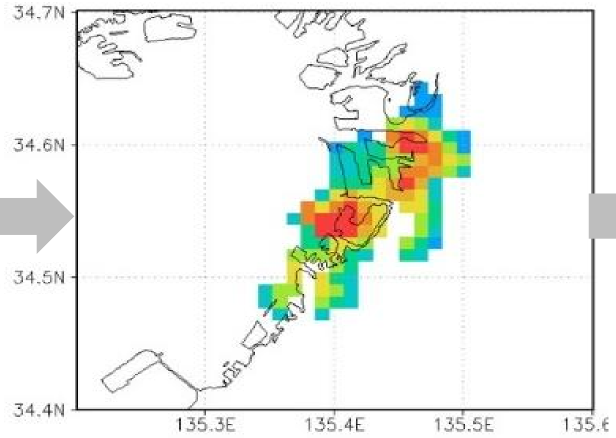


Dual PAWR assimilation: Combining Kobe and Suita Reflectivity Observations

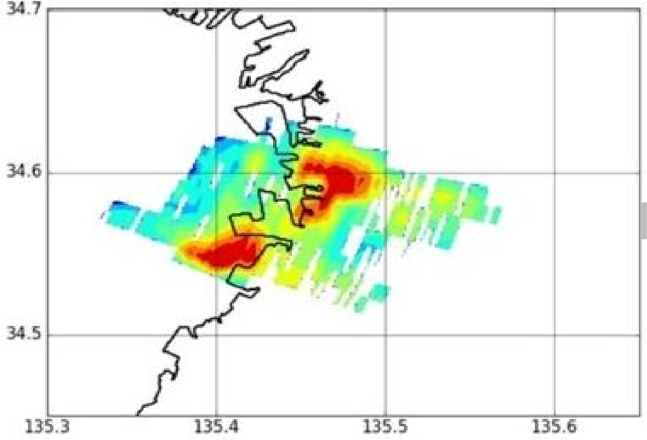
(1) Osaka Radar
Raw Reflectivity Observation



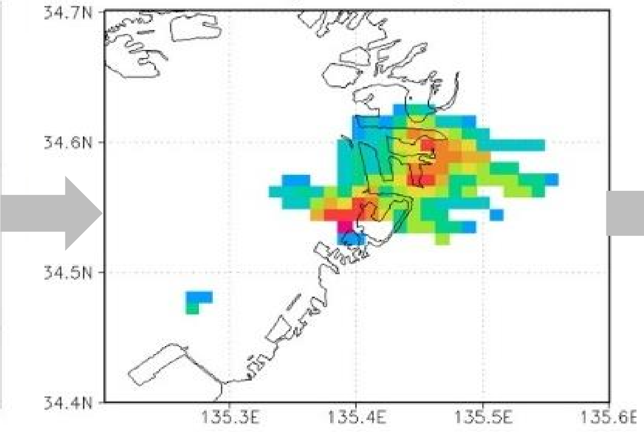
After QC + Superobbing
To 3D Cartesian Grid
(**1km resolution**)



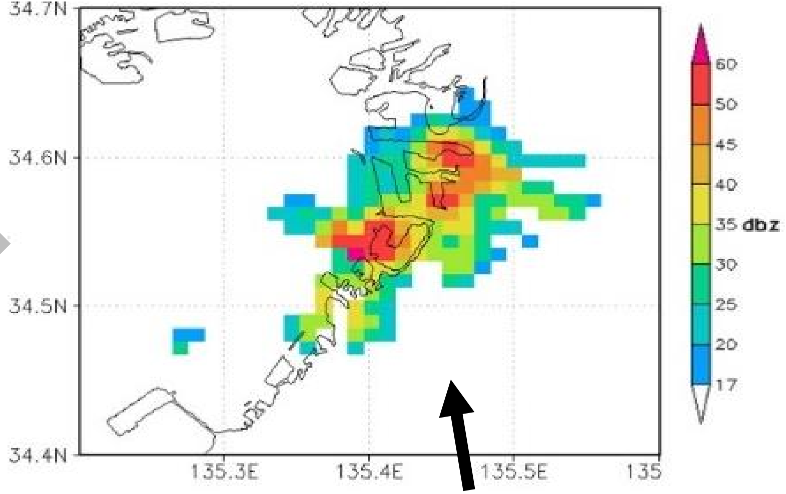
(2) Kobe Radar
Raw Reflectivity Observation



After QC + Superobbing
To 3D Cartesian Grid



Dual-PAWR Combined Reflectivity Field



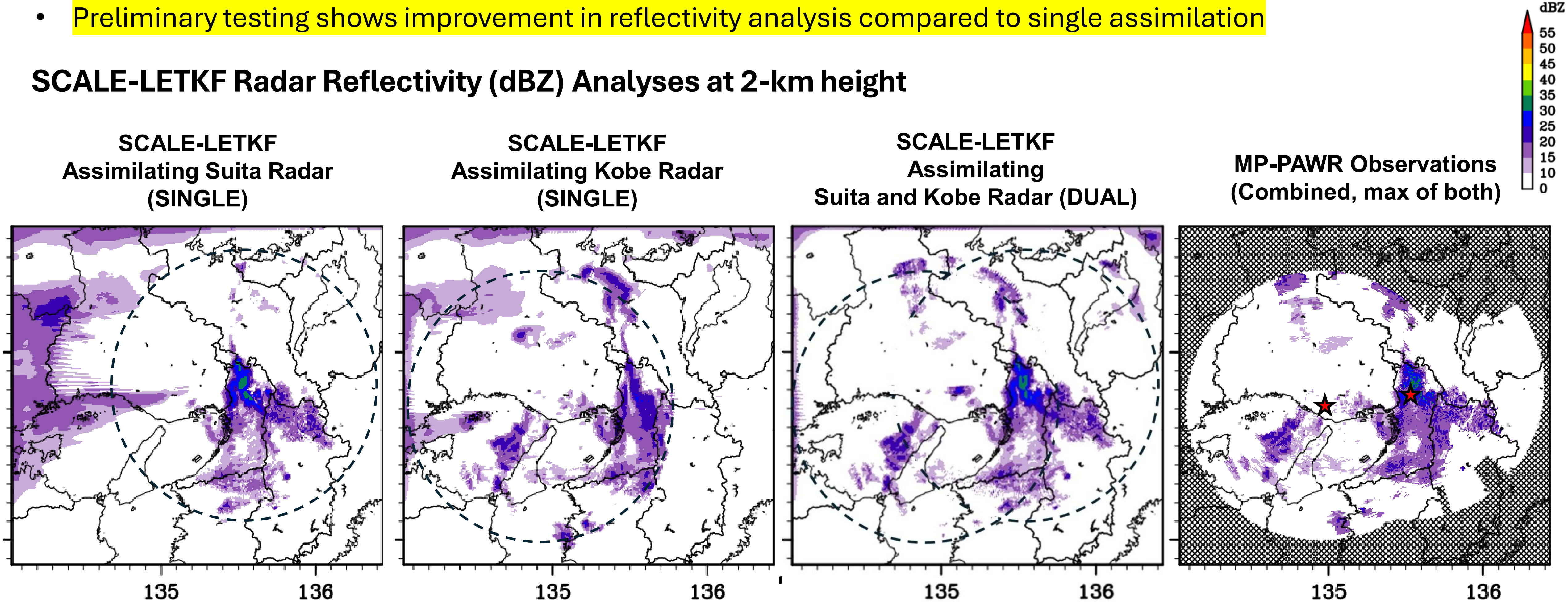
This method created new dataset that combines both radar observations

Works but time consuming – real-time system needs faster solution

Results: Dual MP-PAWR assimilation

- Work to assimilate dual radar observations within the SCALE-LETKF ongoing
- Currently we assimilate Vr x 2 everywhere but Ze x1 at each grid
- Preliminary testing shows improvement in reflectivity analysis compared to single assimilation

SCALE-LETKF Radar Reflectivity (dBZ) Analyses at 2-km height



SCALE-LETKF
Assimilating Suita Radar
(SINGLE)

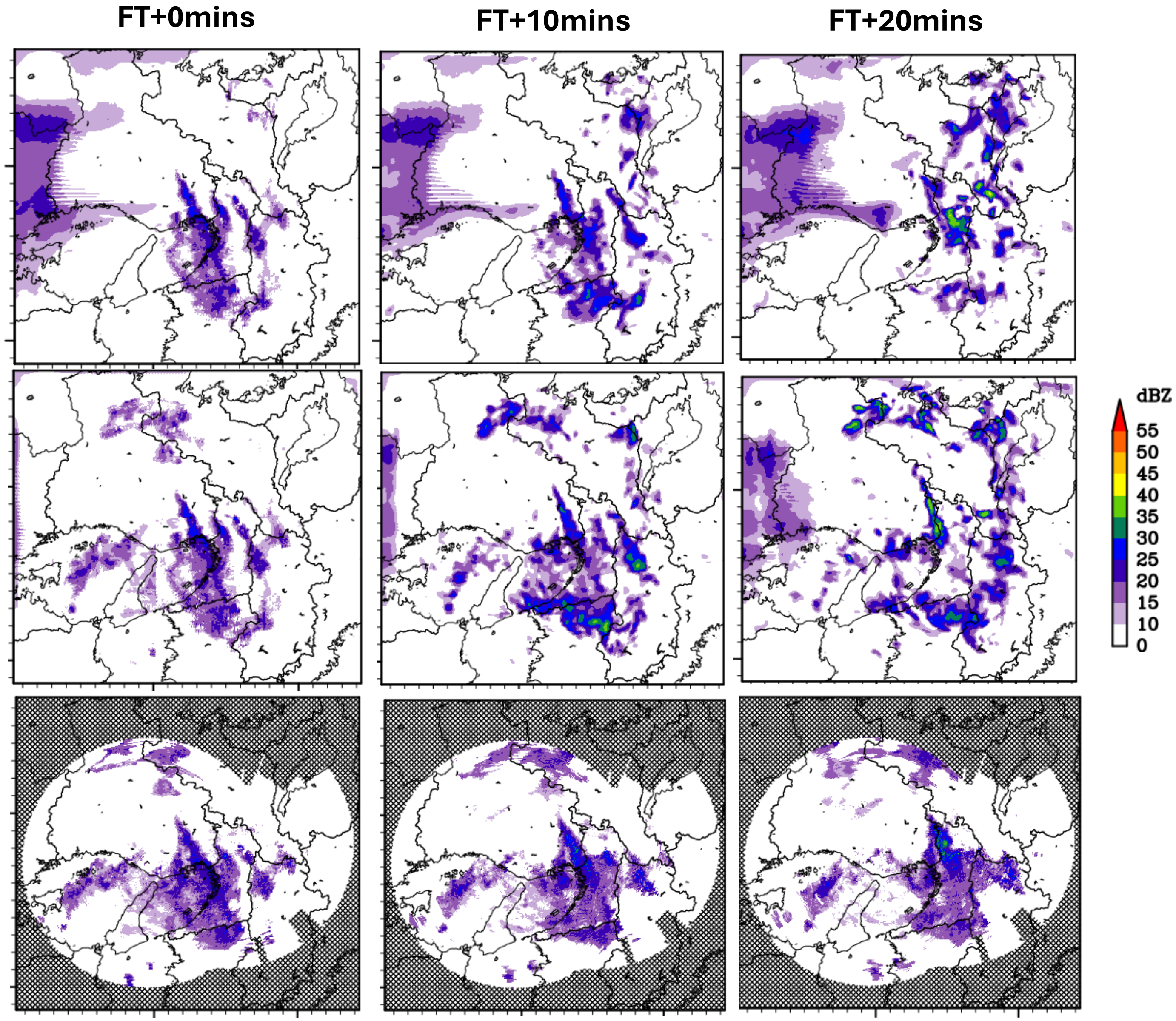
SCALE-LETKF
Assimilating Kobe Radar
(SINGLE)

SCALE-LETKF
Assimilating
Suita and Kobe Radar (DUAL)

MP-PAWR Observations
(Combined, max of both)

Results: Dual MP-PAWR assimilation

Radar Reflectivity (dBZ)
Forecasts at 2-km height



Single MP-PAWR
SCALE-LETKF Assimilating
Suita Radar
(Ze, Vr)

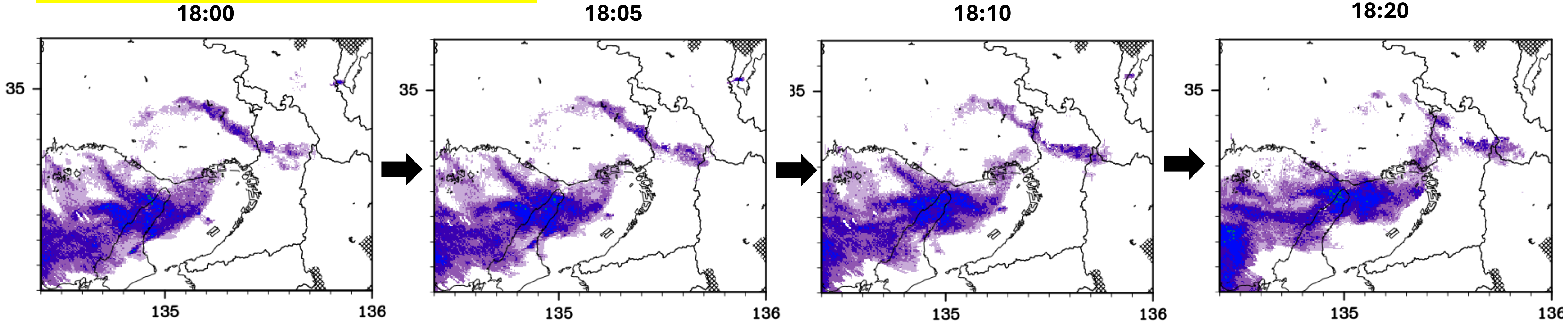
Dual MP-PAWR
SCALE-LETKF Assimilating
Suita and Kobe Radar
(Ze, Vr)

RADAR OBSERVATIONS
(Combined max)

Results: Dual MP-PAWR assimilation

Radar Reflectivity (dBZ) at 2-km height

RADAR OBSERVATIONS (Combined max)

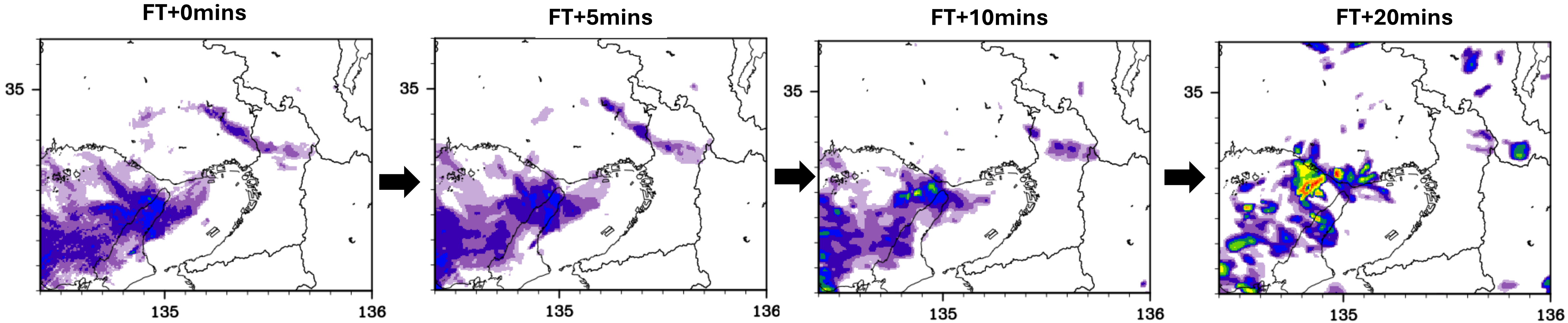

18:00

18:05

18:10

18:20

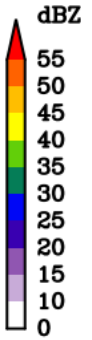
SCALE-LETKF Dual MP-PAWR Assimilating Suita and Kobe Radar (Ze, Vr)


FT+0mins

FT+5mins

FT+10mins

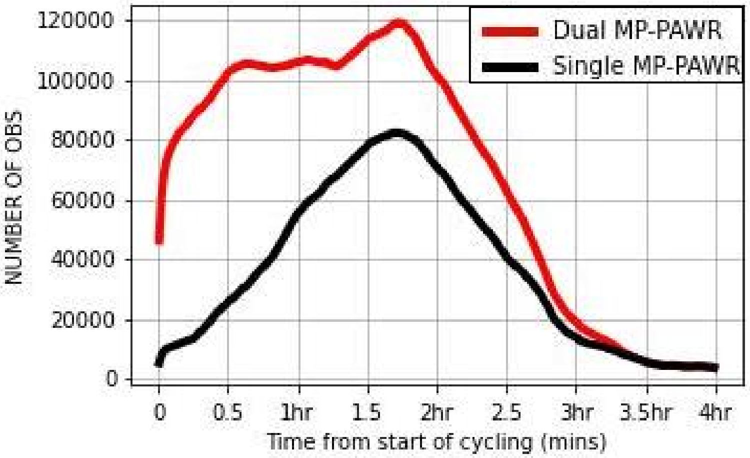
FT+20mins



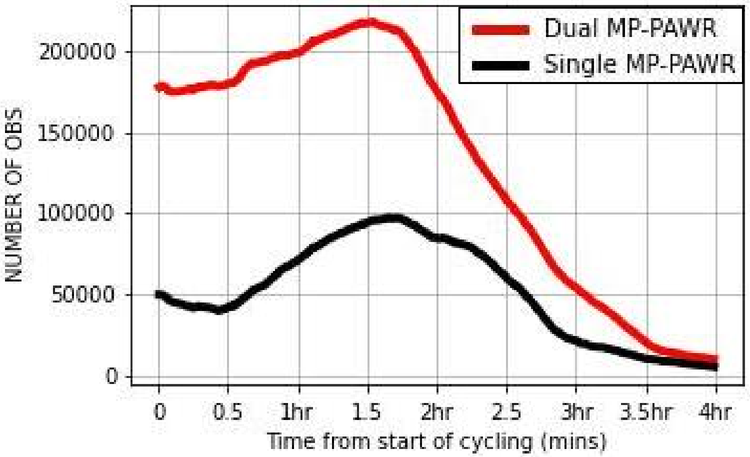
Results: Number of Obs, Processing Time

x2-3 # of obs assimilated during periods of heavy rainfall

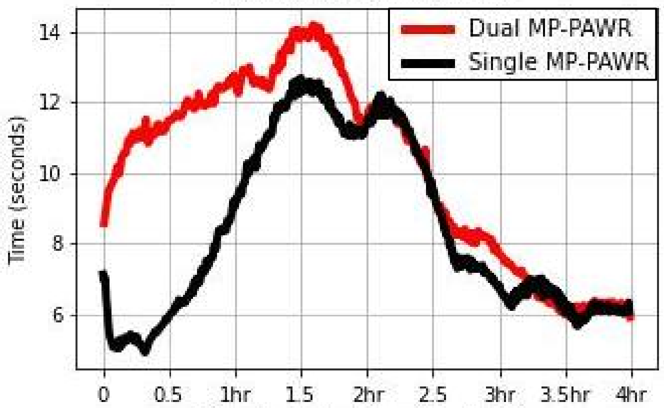
REFLECTIVITY OBSERVATIONS ASSIMILATED



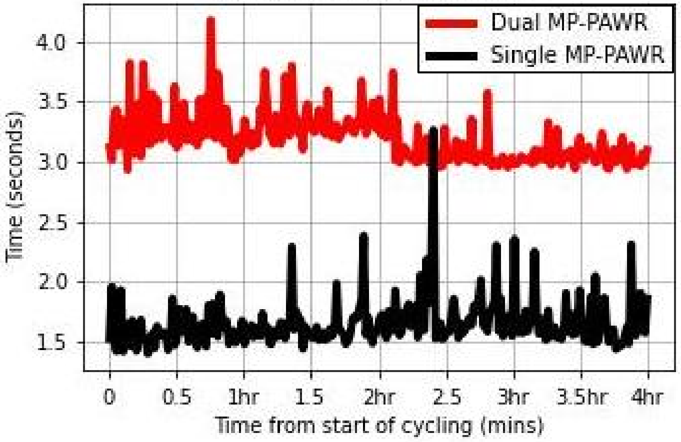
DOPPLER VELOCITY OBSERVATIONS ASSIMILATED



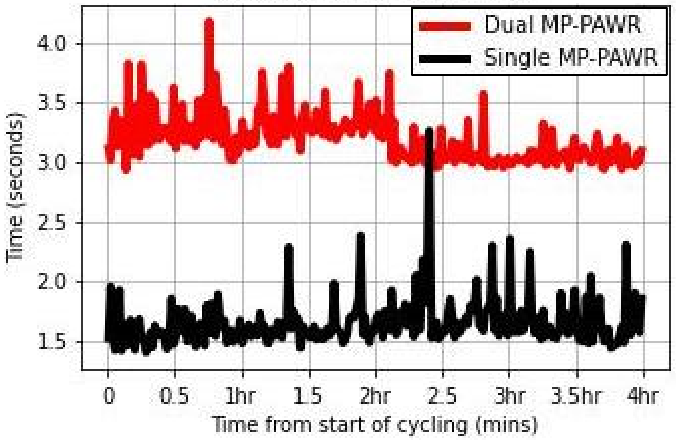
DAS LETKF PROCESS TIME



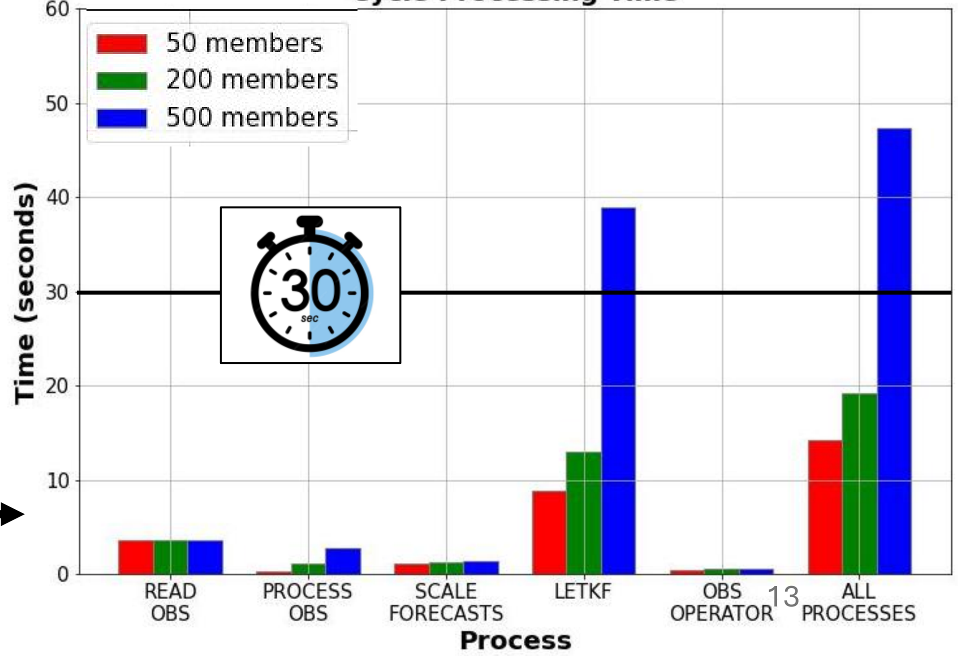
READ_OBS PROCESS TIME



WRIT_ANAL PROCESS TIME



Cycle Processing Time



500-member ensemble currently takes >30 seconds →

Summary and Future Plans

- Successfully assimilated observations from 2 MP-PAWR into the SCALE-LETKF real-time NWP system
- Improved analysis of radar reflectivity field compared to assimilation of single radar data
- Development of the methodology to assimilate dual reflectivity datasets is ongoing (max value in COR)
- Investigate impact of dual wind data on convective activity development
- Reduce processing time to <30-secs for 1000-member ensemble
- Full demonstration planned during Osaka Expo 2025

Challenges for Radar DA

- Although assimilating radar data (reflectivity [Z] and radial velocity [V_r]) can result in the notable correction of precipitation and wind components, the adjustment of temperature and humidity fields may not be optimal
- May need to assimilate other moisture information, as this has shown to improve radar DA in other studies
- Time and spatial correlations with MP-PAWR need to be considered in R matrix
- Improvement needed for initial and boundary conditions
- Build up of model instability leading to generation of spurious convection and rapid intensification
- Spectral nudging technique shown to reduce errors in dynamic downscaling (Waldron et al., 1996; Miguez-Macho et al., 2004; Feser and von Storch, 2008; Cha et al., 2011; Ma et al., 2016)

SCALE-LETKF vs Nowcasts

- Unlike the JMA nowcast, the SCALE-LETKF system successfully predicts the rapid development of small convective cells
- The SCALE-LETKF system applies a physics-based NWP model, so that it could predict the rapid development of the small convective cell

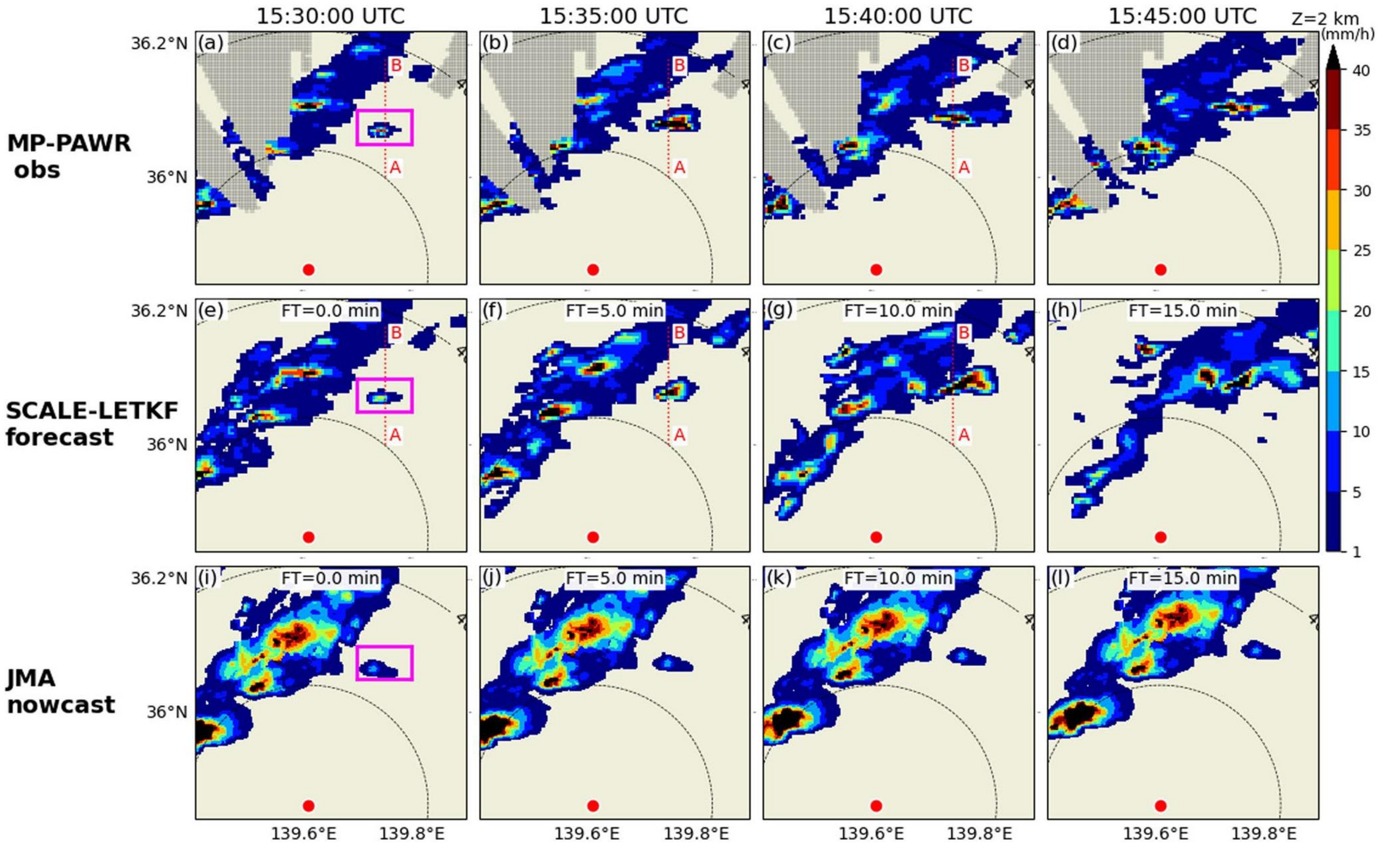
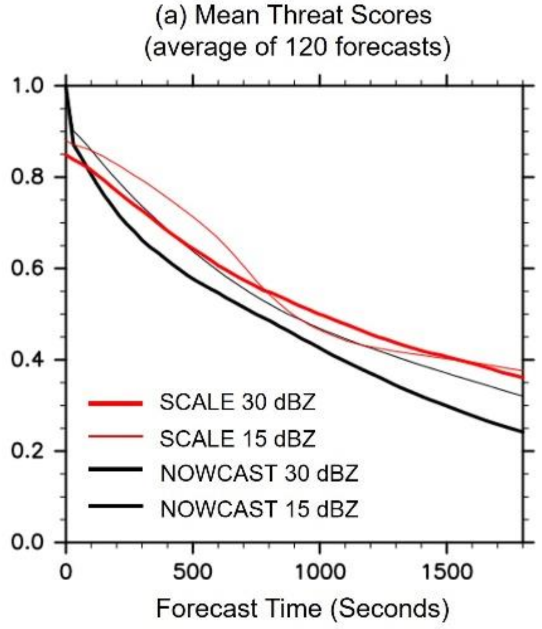


Figure 1. Horizontal maps of the rainfall intensity from the (a)–(d) multiparameter PAWR (MP-PAWR) observations, (e)–(h) SCALE-LETKF forecast, and (i–l) Japan Meteorological Agency (JMA) nowcast valid at (a, e, and i) 15:30:00, (b, f, and j) 15:35:00, (c, g, and k) 15:40:00, and (d, h, and l) 15:45:00 UTC, 24 August 2019. The SCALE-LETKF forecast and JMA nowcast have been initiated at 15:30:00 UTC, 24 August 2019. Red circles: location of the MP-PAWR. Gray dashed circles:

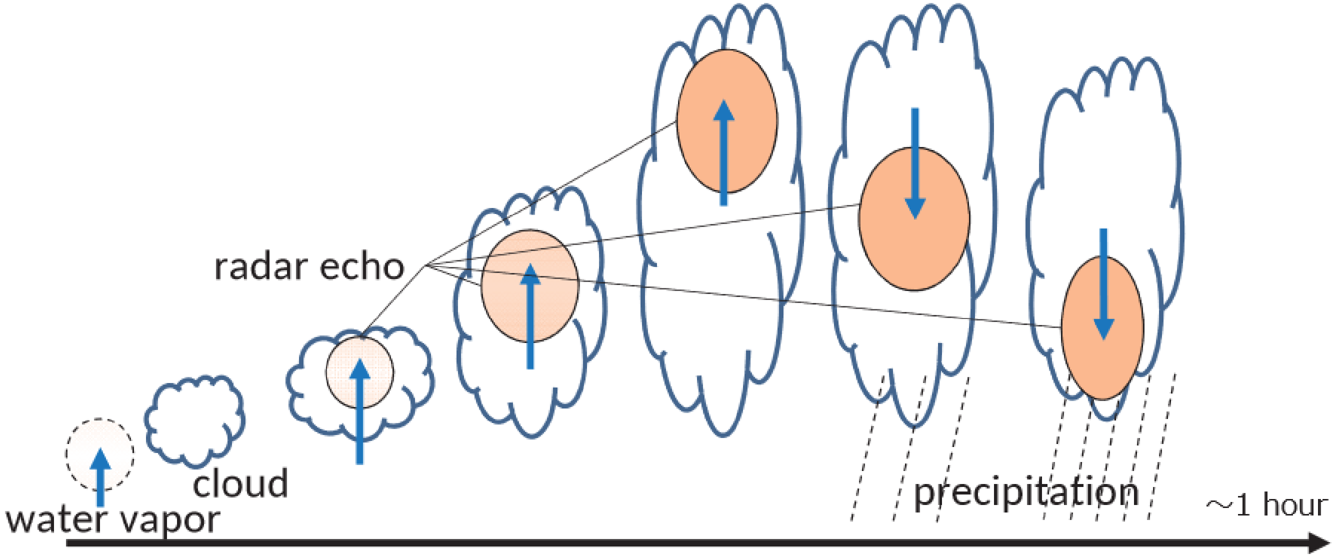


Advantage of 30-s-Updating Numerical Weather Prediction With a Phased-Array Weather Radar Over Operational
Nowcast for a Convective Precipitation System - T. Honda 1,2 , A. Amemiya 1,3 , S. Otsuka1,3,4 , J. Taylor 1,3 , Y. Maejima1,3, S. Nishizawa1 , T. Yamaura1,5 , K. Sueki1,3 , H. Tomita1,3 , and T. Miyoshi1,3,nowcasts? GRL 2022

SCALE-RM

How does the SCALE model work?

- The three-dimensional (3D) Cartesian grid system based on actual distance
- 2D domain decomposition by Message Passing Interface (MPI) communication
- Several map projections commonly used
- Domain nesting system (one-way, i.e., data transfer from parent domain to child domain.)
  - – On-line nesting: concurrent execution of multiple domains).
  - – Offline nesting: execution of computation in an inner domain after that in an outer domain.



SCALE-RM Schemes 1

Cloud microphysics

- Tomita (2008) cloud microphysics scheme is adopted in all domains (Six-class one-moment bulk scheme)
- This scheme assumes that the particle size distribution function is expressed only by mass concentration.
- 5 categories of water: cloud, rain, ice, snow, and graupel.

Turbulence

- The sub-grid scale turbulence model is for representing energy cascade to the sub-grid scale due to the advection terms in Large-eddy simulations (LESs)
- Smagmorinsky turbulence scheme (Lilly, 1962; Smagorinsky, 1963) is used

Radiation

- Model simulation radiation TRaNsfer code X (Sekiguchi & Nakajima, 2008)
- A k-distribution-based broad-band radiation transfer model

Surface Flux scheme

- The surface flux scheme calculates momentum, heat and moisture fluxes at the bottom atmospheric boundary
- COUPLE: Merge surface fluxes from ocean, land, and urban models

Urban model: a single-layer canopy model (Kusaka et al., 2001)

SCALE-RM Schemes 2

Land Model

- The land model consists of two main parts, i.e., an update of the state of the land surface, and calculation of fluxes at the interface of atmosphere and land
- Heat diffusion/bucket model used

Ocean Model

- Ocean condition is fixed to the initial condition. Number of vertical levels is 1

JMA MSM and NCEP GFS Land data

<JMA MSM>
(*for atmospheric 3D variables – 2D surface variables are included but not used)
Format: grib2
Domain size: 22.4N-47.6N, 120E-150E
Grid: 0.1 (lat) x 0.125 (lon) regridded from the original 5-km grid
Levels: 1000, 975, 950, 925, 900, 850, 800, 700, 600, 500, 400, 300, 250,200,150,100 hPa
Variables: GPH, U, V, W, T, RH (up to 300 hPa)
Temporal resolution: 3h
Forecast duration:39h (78h when initial time is 00Z or 12Z)
Refresh: 3h
Latency: ~2.5h

<NCEP GFS>
(*for land 2D variables)
Format: grib2
Domain size: global
Grid: 0.5 (lat) x 0.5 (lon) regridded from the original ~13km grid
Variables: land-sea mask, land surface temperature, soil temperature, soil moisture
Temporal resolution: 6h
Forecast duration:16d
Refresh: 6h
Latency: ~9h

Achieving real-time DA

- To perform D4 in real time, we merge the SCALE-RM and LETKF in D4 into a single executable binary and continuously run as a single computation job. As a result, data transfer between the SCALE-RM and LETKF is performed by a memory copy instead of a file I/O. Furthermore, the MPI initiation is not required every 30 s. Without this implementation, D4 could not be real-time

- Single precision for LETKF, SCALE-RM and eigenvalue solver

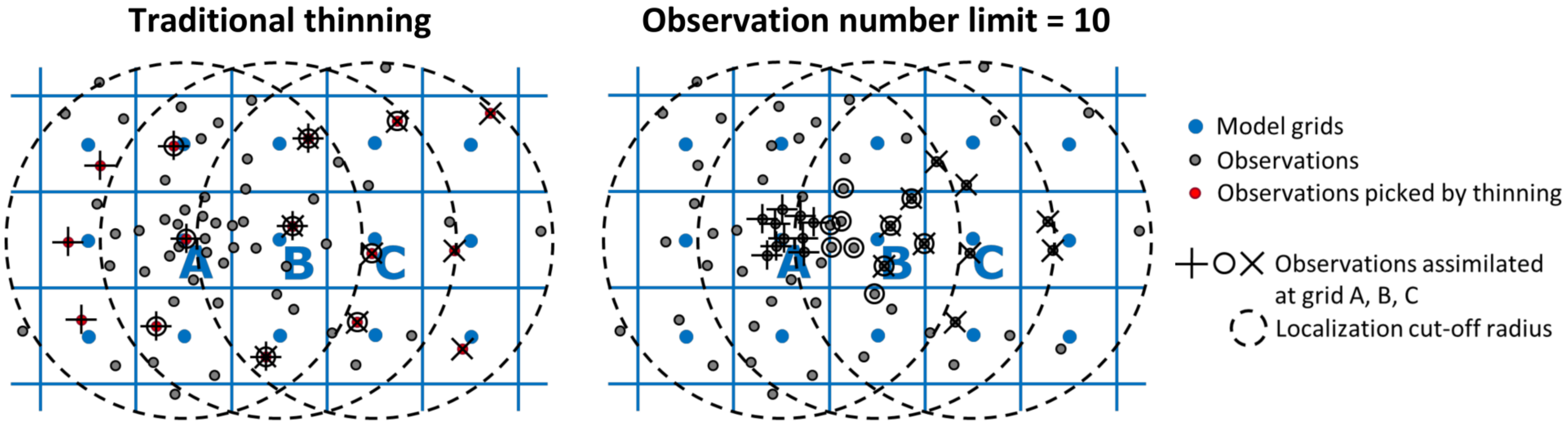
Observation limit

Recent studies indicate that the ensemble size limits the number of observations that can be effectively assimilated by the ensemble Kalman filter (Hamrud et al., 2015; Hotta & Ota, 2021; Schraff et al., 2016)

So we set the observation number limit for each grid at a total of 200 (100 for radar reflectivity and 100 for Doppler velocity).

Limit the number of observations used at each grid point for each observation type.

Observations **spatially closest to the analyzed grid** are selected.



Outer domain ensemble generation

We follow the method used in Necker et al. (2020,*QJRMS*).

MSM data with the same format for summer months of 10 years between 2011-2020 are collected and used as a database.

An ensemble member is generated as a time series, adding perturbation to the original time series of MSM forecast. Perturbation is generated as a difference between two forecasts from different initial times in a season same with the original forecast. A factor parameter is used to control the amplitude of the perturbation.
(ensemble member forecast) = (original forecast) + factor * [(past forecast 1) - (past forecast 2)]

After the calculation, negative fixer and supersaturation fixer are applied to perturbed water vapor values.

Land data (soil temp, soil moisture etc) is the same for each member

Observation operator

The observation operator for the PAWR calculates radar reflectivity Ze [mm6 /m3] from mass density W [g/m 3] of each hydrometeor category in a model output. The cloud microphysics scheme currently used in SCALE-RM is a single moment 6-caterogy scheme, with 3 categories for precipitation particles, - rain, snow, and graupel (Tomita 2008).

The Ze − W relation is theresult of radiative scattering processes by the mixture of precipitation particles with different size distribution. In the observation operator, it is approximated as a superposition of exponential functions as follows.

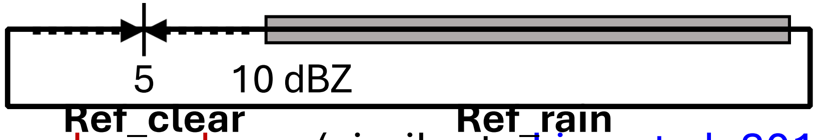
$$Z_e = \alpha_r W_r^{\beta_r} + \alpha_s W_s^{\beta_s} + \alpha_g W_g^{\beta_g},$$

where Wr , Ws and Wg are mass density for rain, snow, and graupel, respectively. The coefficients α and β for each precipitation category are obtained by a linear fitting of log Ze − log W relation, which is simulated offline by a radar simulator.

- Observation operator to assimilate reflectivity based on coefficients by Amemiya (2020)

Setttings

- Superob to model resolution (use only the data below 11 km).
- Define **Ref_rain**: raw Ref >= 10 dBZ, **Ref_clear**: raw Ref < 10 dBZ
- Set all **Ref_clear** (both observation and background) to 5 dBZ. (Similar to Aksoy et al. 2009 but leave a 5-dBZ gap between minimum **Ref_rain** and **Ref_clear**). (Similar to Aksoy et al. (2009), reflectivity data that are lower than 10 dBZ are assimilated as no-precipitation data
- with 5 dBZ.)
- Observation errors: **Ref**: 5 dBZ
  Vr: 3 m/s
- Reject data when [y – H(x)] > 10 x obs error



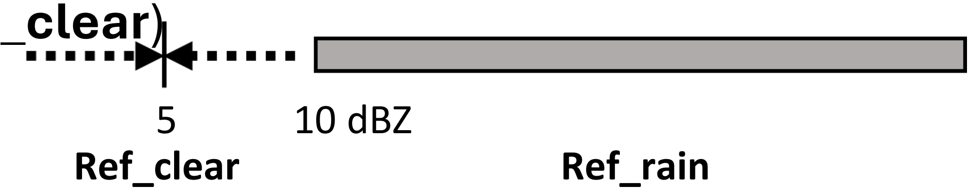
- Reject data when there are too few “raining” (**Ref_rain**) background members: (similar to Lien et al. 2013, 2016 for precipitation assimilation)
  Ref_rain obs: require >= 1 (out of 100) background members having **Ref_rain**
  Ref_clear obs: require >= 20 (out of 100) background members having **Ref_rain**
- Limit number of observations used per grid (Hamrud et al. 2015): Max = 100
- Relaxation to prior spread (Whitaker and Hamill 2012): α = 0.95
- Covariance localization:
  Horizontal (**Ref_rain** and **Vr**): 2 km
  Horizontal (**Ref_clear**): 2 km
  Vertical (all): 2 km

Raining / clear-sky reflectivity

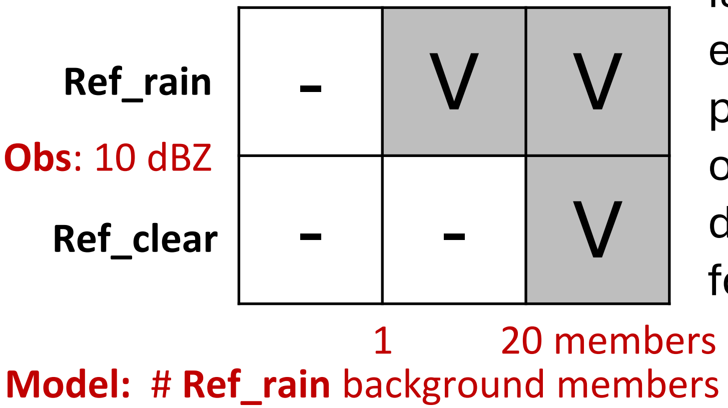
- **Ref_rain:** raw Ref >= 10 dBZ
  Ref_clear: raw Ref < 10 dBZ

- "Clear reflectivity shift":
  - Set all **Ref_clear** (both observation and background) to 5 dBZ

(Similar to Aksoy et al. 2009, but leave a 5-dBZ gap between minimum **Ref_rain** and **Ref_clear**)



- Reject data when there are too few raining members in the background:
  - For **Ref_rain** obs, require >= 1 (out of 100) background members having **Ref_rain**
  - For **Ref_clear** obs, require >= 20 (out of 100) background members having **Ref_rain**



Ref_rain	-	V	V
Ref_clear	-	-	V

(Similar to Lien et al. 2013, 2016, 2017 for precipitation assimilation)

Earlier studies on the assimilation of precipitation observations (Lien et al., 2013, 2016) indicated that it is important to use the number of precipitating ensemble members as a threshold of QC. Therefore, we assimilate precipitation radar reflectivity data when the number of precipitating ensemble members is ≥5. The no-precipitation radar reflectivity data are assimilated if the number of precipitating ensemble members is ≥1. If the number of precipitating ensemble members is zero, no-precipitation reflectivity observations are discarded. These QCs are applied for each reflectivity observation

Questions

1) Why do we use 1000-member ensemble?

The mesoscale error covariances in radar DA are very flow-dependent

2) Is radar reflectivity a nonlinear variable?

Yes. This is an issue

3) What is reflectivity?

It’s a measure of the return intensity of the microwave radiation pulse that is sent out

4) How do we calculate rainfall intensigy for the observations and SCALE-LETKF

Via the Z-R relationship

5) What is a one moment microphysics scheme?
One that is based on mass of particles