Super high-resolution mesoscale weather prediction

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Abstract. A five-year research project of high performance regional numerical weather prediction is underway as one of the five research fields of the Strategic Programs for Innovative Research (SPIRE). The ultimate goal of the project is to demonstrate feasibility of precise prediction of severe weather phenomena using the K-computer. Three sub-themes of the project are shown with achievements at the present and developments in the near future.

1. Introduction

Accuracy of numerical weather prediction (NWP) in world advanced weather forecast centers has been considerably improved recently. For example, the quantitative precipitation forecast (QPF) performance of the operational mesoscale model (MSM) of the Japan Meteorological Agency (JMA) has been increased almost twofold in threat scores for moderate rains in the recent ten years [1]. Continuous advance in numerical modelling and data assimilation techniques has contributed to the achievement. However, many difficulties remain in numerically predicting small scale severe weathers (e.g., torrential rains, local strong winds, tornadoes) with specifications of intensity, location and timing. Spatial and temporal scales of these severe phenomena are generally small, and evolution of these phenomena is sometimes very sensitive to trivial differences in the initial condition, because they often occur in convectively unstable atmospheric conditions. To overcome above problems, data assimilation and the ensemble forecast with the cloud-resolving resolution are required, as well as development of high accuracy high-resolution atmospheric models.

As one of the sub-subjects of the Field 3 of the Strategic Programs for Innovative Research (SPIRE), a research on high performance regional NWP has been carried out since April 2010. The sub-subject has the following three themes:

1) Development of cloud resolving 4-dimensional data assimilation systems,
2) Development and validation of a cloud resolving ensemble analysis forecast system, and
3) Basic research using very high-resolution atmospheric models.
2. Goals of the research subject

2.1. Development of cloud resolving 4-dimensional data assimilation systems (by MRI, JAMSTEC, NPD, NIED, DPRI and ISM)

The goal of the first theme is to dynamically predict deep convection and associated local severe weathers by modifying the initial condition of the cloud-resolving model. So far, high resolution data assimilation methods based on the JMA nonhydrostatic model (NHM; [1-3]) have been developed, and applied to case studies of cloud resolving forecast experiments of local precipitation (e.g., NHM-4DVAR [4]) and NHM-LETKF [5]). Dense observation data such as radar reflectivity, Doppler radar radial winds, GPS-derived total precipitable water vapor data are assimilated in storm scale to obtain more accurate initial conditions. A two-way nested LETKF (figure 1), which employs a low resolution LETKF as a no-cost smoother to supply lateral boundary conditions to inner high resolution LETKF, has been developed [6] and is tested for the K-computer. A displaced ensemble variational assimilation method has also been developed and tested for a data assimilation experiment on satellite microwave imager data [7]. As a more ambitious trial for the K-computer, development of a particle filter is underway at ISM [8].

Another storm scale LETKF system and a hybrid ensemble-variational data assimilation system for deep convection based on a cloud resolving model CReSS [9] are also under development at DPRI [10] and NIED [11], respectively.

Figure 1. Concept of the two-way nested LETKF. After Seko et al. [6].
2.2. **Development and validation of a cloud resolving ensemble analysis and forecast system (by MRI, JAMSTEC, NPD, DPRI, Kobe University and Tohoku University)**

Ensemble prediction is another approach to extend the predictability of meteorological phenomena. MRI and its collaborators once participated in the international intercomparison of mesoscale ensemble prediction which was held in the WWRP Beijing Olympics 2008 Research and Development Project (B08RDP [12-14]). Initial perturbation methods and effect of lateral boundary perturbations were investigated for the mesoscale ensemble forecast with a horizontal resolution of 15 km [15, 16].

In SPIRE, the goal of the second theme is to demonstrate the plausibility of the probabilistic quantitative forecast of severe weathers for disaster prevention by cloud resolving ensemble NWP. An NHM-LETKF system using the incremental approach method developed at NPD has been tested [17] and applied to the K-computer. This ensemble data assimilation system shares observation operators with the JMA’s operational nonhydrostatic 4DVAR system (JNoVA), while its target is the quantitative probabilistic forecast for heavy rainfalls using cloud resolving ensemble prediction. Duc et al. [18] applied the LETKF system to the ensemble numerical simulation of Myanmar cyclone Nargis with the K-computer.

Cloud resolving (2 km) ensemble forecast experiments were performed for the summers of 2010 and 2011 as the test trials using the MRI’s super computer and were validated with observed rainfall [19]. The JNoVA 4DVAR analyses were used as the initial conditions, while the JMA one-week ensemble prediction was used as the lateral boundary perturbations. Saito et al. [20] applied this system to the 2011 Fukushima-Niigata heavy rainfall and discussed the predictability of the event. Origuchi et al. [21] tested the similar system for the heavy rainfall case of typhoon T1112 (Talas), and compared with the LETKF-derived analyses and perturbations. Results of the probabilistic forecast are validated and used as the input data for application systems for disaster prevention such as the ensemble flood forecasting at Kobe University [22].

As the ultra high resolution forecast system, the LETKF nested system was linked with a computational fluid dynamics (CFD) model with a horizontal resolution of 10 m at Tohoku University [23]. Figure 2 shows the model result that captures well an invasion of the sea breeze front and the 3-dimensional structure of horizontal convective rolls over Sendai downtown with resolved buildings.

![Figure 2. The invasion of sea breeze over Sendai downtown. The warm/cold air is plotted in red/blue, respectively. Near surface winds are shown by yellow vectors. After Chen et al. [23].](image)

2.3 **Basic research using very high resolution atmospheric models (by JAMSTEC, MRI, NPD, AORI, Tohoku University, DPRI, HyARC and NDA)**

In this theme, uncertainties of the current atmospheric models due to subgrid scale parameterization in physical processes are evaluated using very high-resolution numerical models. Uncertainties of the
bulk cloud microphysics scheme for cloud resolving models are evaluated using the spectral BIN method models (e.g., [24, 25]).

To challenge the ‘grey zone’ problem in atmospheric models with horizontal resolutions around 1 km, so-called ‘Terra Incognita’, the planetary boundary layer parameterization scheme is evaluated by the large eddy simulation (LES) models [26]. Figure 3 shows an example of LES simulation by AORI with a grid distance of 50 m. To reduce all-to-all communications in the MPI parallelization, Fast Fourier Transform to solve the Poisson equation is conducted within a single computational node of the K-computer. Development of regional versions of NICAM (Nonhydrostatic ICosahedral Atmospheric Model) is also underway at JAMSTEC to utilize the model for very high-resolution experiments [28].

High-resolution simulations of typhoons and tornadoes are conducted to study mechanisms of their development (e.g., [29, 30]).

Figure 3. Horizontal distribution of turbulent mixing length (relative values) with a horizontal subfilter size of 2 km estimated by LES. Isolines denote upward vertical velocity (m/s). After Ito et al. [27].
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Appendix

List of acronyms

- AORI: Atmosphere and Ocean Research Institute/University of Tokyo
- CReSS: Cloud Resolving Storm Simulator
- DPRI: Disaster Prevention Research Institute/Kyoto University
- HYARC: Hydrospheric Atmospheric Research Center/Nagoya University
- ISM: Institute of Statistical Mathematics
- JAMSTEC: Japan Agency for Marine-Earth Science and Technology
- LETKF: Local Ensemble Transform Kalman Filter
- MRI: Meteorological Research Institute/Japan Meteorological Agency
- NDA: National Defense Academy
- NIED: National Research Institute for Earth Science and Disaster Prevention
- NPD: Numerical Prediction Division/Japan Meteorological Agency
- WWRP: World Weather Research Programme
- 4DVAR: Four dimensional variational (data assimilation)

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